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Study and implementation of a middle-sized rocket motor bench test system

Final Master Thesis - Report

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Thanks to my family, Kelly and all the friends that supported me while doing this thesis.

Also thanks to my teacher Jaume for presenting me with this opportunity and his help in the development of the test stand.

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Introduction

It is one thing to study about rocket propulsion, performance and thermodynamics, but it is another to test it in a real scenario and to know how much thrust did a specific motor generate. What is the shape of the thrust curve in time? Does the thrust vary with different types of fuel types and geometry of the grain? Does the ignition affect the burn? What is the total impulse and how does the specific impulse vary compared to the design values? What information can be obtained from the data generated on a static test stand and how can a rocket motor's performance be analyzed by it?

It is all this questions that are tried to be answered in a static test stand, and such a test stand is the center of this study.

1.1 Abstract

This thesis describes a project of design, construction and evaluation of a middle-sized rocket test bench.

This project has been developed by the author and the professor without any external funding and with the use of off the shelf components in as many parts as possible.

Also, this project has been developed from the inspiration and passion of the teacher and author in this field and for practical use in the future with small and middle-sized model rocket motors.

1.2 Objective

In the rocket industry it is very important the generation and acquisition of the thrust force created by a rocket motor for the following plotting and analysis.

With this data, the graphical representation of the thrust curve can be made and so the performance of a motor be evaluated and compared to those of other motors.

In order to be able to obtain this data it is necessary to build a test bench or stand.

This project has its objective in the designing and building of such a test stand.

The intended use for this test bench is that of model rocketry motors testing.

1.3 Justification

This thesis originated from an idea proposed by the teacher and supported by the student. During the development of a course in the final year of the master, an activity was carried out which consisted in the launch of a rocket developed in class and the assessment of its performance compared to the previously calculated. This activity was made in conjunction with an association called Spain Rocketry which offered us assistance and also launched their own rockets.

By the end of the course, it was found by the student that this was a very rewarding experience and decided to ask the teacher to further investigate the subject by doing a thesis.

It was found that a very interesting project in order to assess the performance of model rockets would be that of creating a test bench to assess the performance of small to medium rocket motors. That way, it could be used by the association to create new rocket motors with in-house developed solid fuel or to test the performance of commercially available rocket motors.

For this reason this project was started and carried out. It would be important that this test bench would be made in-house with off the shelf products and with a lower price than test stands available for purchase.

1.4 Requirements

In order to define the functions and capabilities of the test stand to be designed and built, it is necessary to assert certain requirements that force the project to fulfill certain necessities by the end of it.
These mandatory requirements are as follows:

1. Cost

   1.1. This project must be on a budget, which means that it must be affordable to an amateur association or a person. The restrictions of the budget will mean that the total price should be around or less than a 1000 euros limit. This limit comes from the fact that the resulting product of this project will be owned by the person and will not be funded by a private business or the university.

2. Design

   2.1. Data Aquisition System (DAS) and Load Cell

      2.1.1. This test bench will posses a DAS capable of obtaining a high enough sample data rate to which the performance of the rocket can be precisely calculated. This will be defined by a number of samples per second of higher or equal to 8000 SPS.

      2.1.2. The number of bits of the signal output from the load cell to the DAS will have to be accurate enough so that a good range and resolution of the thrust curve can be obtained. This will be reflected in a requirement for a 16 bit or more ADC module.

      2.1.3. The load cell will have to output its signal in the mV scale to the DAS, this means that the DAS will need to posses a signal amplifier and an analog to digital ADC converter.

      2.1.4. The load cell will have to be flexible in the range of possible rocket motors to be tested, this means that the maximum load capable to be used in the load cell will limit the size of the rocket motor tested. For this bench a load cell of at least 9800 Newtons has been required, this will allow the test bench to support a variety of rocket motors forms, from small to middle sizes.

      2.1.5. The DAS will be able to record information autonomously by having some batteries or autonomous power supply to receive data for a period of time of no less than 10 minutes without interruptions.

2.2. Structure

2.2.1. The structure will have to be resilient enough for the test stand to be able to be used a number of times without the deformation of any of its parts.

2.2.2. The whole structure will have to be adapted to be moved easily by transportation vehicles such as a car. This could be performed by having moving, folding and/or extendable parts, or by having a structure that can be dismounted into smaller parts by the means of screws and bolts, for example.

2.2.3. The bench must be able to accommodate rocket motors with up to, at least, a diameter of 150 mm.

2.2.4. The maximum length of any given part must be of 1.6 meters.

2.2.5. The maximum weight of any given part must be of 30 kg.

2.2.6. The maximum weight of the test stand must be of 800 kg.

3. Safety

3.1. The operation of this test bench will have to be secure enough so that no personal injuries or material damage is occurred during the operation.

3.2. The structure of this bench will have to posses some kind of passive protection for the users in case anything wrong should occur and any piece from the subjection or the motor comes loose and is fired towards the users. For this risk, the bench might use a protective screen or some kind of similar device.

3.3. The operating procedures to use the bench should be designed in order to eliminate or mitigate/minimize any risks inherent to the ignition of rocket motors.

In order to verify the fulfillment of each of the requirements a table of verification means is presented as follows:

Table 1.1: Verification of the requirements.

Requirement	Verification procedure
Re.: 1.1	Creation of budget and budget check of total price on the project.
Re.: 2.1.1	Design revision and check on component specifications. Performance test in a real scenario.
Re.: 2.1.2	Design revision and check on component specifications. Performance test in a real scenario.
Re.: 2.1.3	Design revision.
Re.: 2.1.4	Design revision and check on component specifications. Simulation test. Performance test in a real scenario.
Re.: 2.1.5	Design revision. Performance test in a real scenario.
Re.: 2.2.1	Simulation and performance test in a real scenario.
Re.: 2.2.2	Design revision and test in a real scenario.
Re.: 2.2.3	Design revision and construction check on dimensions.
Re.: 2.2.4	Design revision and construction check on dimensions.
Re.: 2.2.5	Design revision and construction check on weight.
Re.: 2.2.6	Design revision and construction check on weight.
Re.: 3.1	Simulation check and safety measures according to normative.
Re.: 3.2	Design revision. Safety measures according to normative.
Re.: 3.3	Design revision and operational procedures listed and according to normative and previous experiences on similar tests and experiences with rocketry.

1.5 Scope

The scope of this project will be constrained to the design and construction of the rocket motor test bench.

The main points of this work will be redacted into a Report that will cover the following topics:

1. Introduction, objective, scope, requirements and justification.
2. State of the art.
3. Design.
   (a) Dimensions.
   (b) Structure.
   (c) Electronics (Data Acquisition).
   (d) Materials.
4. Evaluation of the design.
5. Development and building of the solution.
6. Budget.
7. Conclusions and future perspectives.

The work will also possess the necessary annexes and technical documents of any pieces of the bench that could not be described in detail inside the report.

State of the Art

Rockets have existed for a very long time, historians believe that the Chinese developed the first real rockets around the first century A.D. [31] They were used for colorful displays during religious festivals, similar to fireworks.

Since then rocket technology was developed and new inventions created, until modern rocketry was created at around the start of the 20th century with the publication of what is known as the rocket equation by Konstantin E. Tsiolkovsky. Although his work was unkown outside the Soviet Union, his equation allowed the further development of rocket technology inside russia.

On the other hand, in the early 20th century there were others like Goddard, an american, or Oberth, born in Romania, that were making big developments in rocket technology. Goddard sent the first liquid-fueled rocket aloft in Massachusets in 1926 and Oberth helped develop the V2 rocket during World War 2.

Since then rocket test stands have been a necessity for further research and development of rocket motors as rockets begun to be more and more complex machines.

One example of an early test stand for a small sized rocket motor is the following:

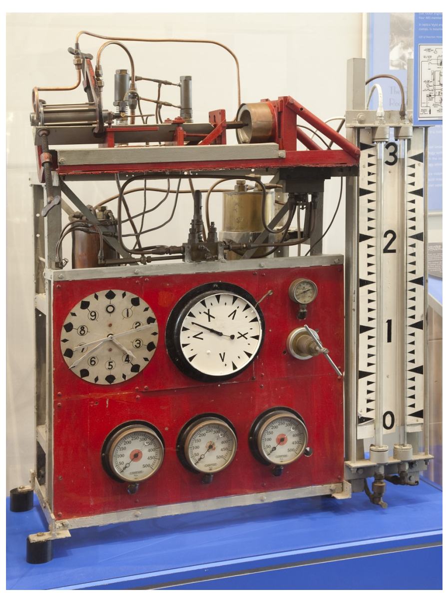


Figure 2.1: Rocket Test Stand No. 2, developed by the American Rocket Society in 1938. It can be observed the analog way of obtaining the thrust data with clocks and meters. [1]

Figure 2.2: Reaction Motors, Inc. M15-G1 rocket engine being tested on the American Rocket Society's Test Stand no.2 in June 1942. [2]

This test stand was built in 1938 by the ARS and used in ground tests of experimental rocket motors. It was capable of obtaining data from rocket motors with a maximum of 200 pounds of thrust capacity (889 N).
This test stand was notably used to prove the effectiveness of regeneratively cooled motors in James H. Wyld's research tests from 1938 to 1941. This success led Wyld to form, with 3 other members of the ARS, the first commercial liquid-fuel rocket company which later built the 6000-pound thrust rocket engine for the Bell X-1, an experimental rocket aircraft that broke the sound barrier in October 1947.

Figure 2.3: Bell X-1. [3]

Nowadays, the modern test stands used by NASA, ESA or other big companies as Space-X have increased in complexity and size and incorporate more modern features and technologies.

For example, the Stennis Space Center is a research facility that originated from the necessity of flight certifying all first and second stages of the Saturn V rocket for the Apollo program. The first static test carried on in this facilities dates back to April 23, 1966 but carried on operating after the Apollo mission was finished. It certified all the engines used to boost the Space Shuttle to low-earth orbit in

1975. Over the years the Stennis Space Center has evolved into a multidisciplinary facility comprised of NASA and more than 40 other resident agencies and continues to operate nowadays. It has facilities with capabilities to test and flight certify from large thrust level engines to smaller thruster and engine testing, as well as subscale testing systems for both commercial and government interests.

Their main test stand is the A-1, first designed to test fire the Apollo Saturn V Second Stage (S-II), and is a fixed-position vertical oriented test stand used for testing liquid rocket engines at sea level conditions. It has a 33 foot diameter opening within the thrust drum and LH and LOX propellant capabilities. It has a thrust measurement capacity of 600.000 lbf [4].

Figure 2.4: A-1 Test Stand at SSC. [4]

During a typical test performed at the A-1 site more than 28 billion bytes of information samples are generated during a 535 second test, with 2 data systems, one for high speed data acquisition and one for low speed transmission. NASA test engines at the A-1 site for 2 main reasons, to confirm expectations of a motor performance under certain conditions and to expand the understanding of how an engine will perform at certain circumstances. For these objectives the data acquisition systems will need to obtain as much data as possible and with accuracy. The A-1 test stand is provided with a hygh speed data acquisition system of 256 channels, each collecting 102.400 samples per second and a low speed system with 512 channels that generate 250 samples per second. All these systems are needed in order to measure every aspect of engine operation such as pressures, temperatures, pump revolutions per minute, thrust and valve function.

Another one of the test stands being used in the Stennis Space Center, a more small sized one, is the E-2 Test Stand.

Figure 2.5: E-2 Test Stand at Stennis S.C. [5]

Here we can see the test of the oxygen preburner component being developed by SpaceX, in a partnership with NASA, for its Raptor rocket engine, which is being built to power flights to Mars. The main objectives of this test of a preburner where to guarantee the reliability of the ignition and the proper temperature distribution for the pump turbines. In total, 76 hot fire tests were completed on the component, totaling 399.36 seconds [32]. This facility was chosen by Space-X for its small size and high-pressure capabilities.

Modern processes of fabrication and the evolution of electronics have allowed the development of smaller and cheaper test stands that can be produced and used by small organizations or individual persons, instead of being only achievable by big corporations or governmental organizations.

One example of a very small and cheap model is the following [6], constructed by using only an arduino and some basic off the shelf materials.

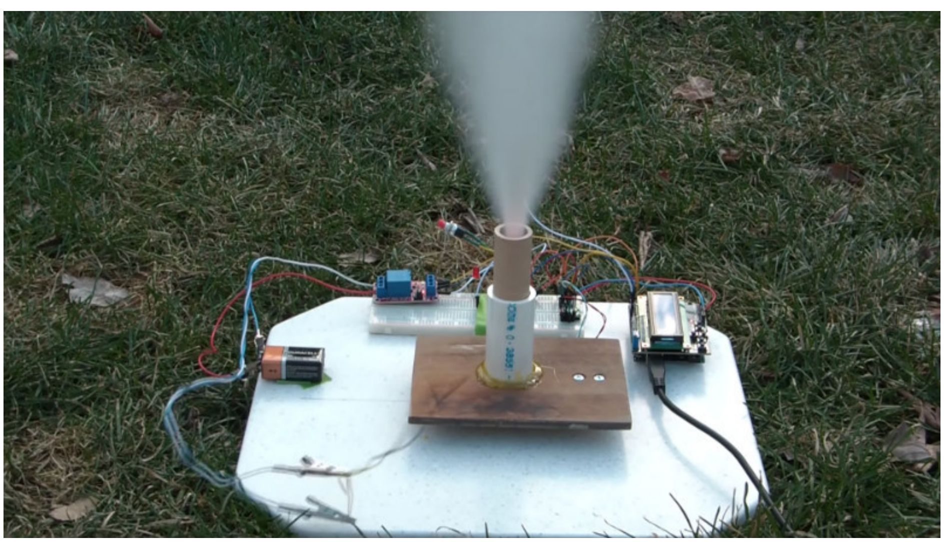


Figure 2.6: Arduino powered rocket test stand. [6]

Here the most basic components of a test stand can be observed:

- Motor support structure
- Load cell
- Power supply for the electronics
- Electronics to process the signal for the DAS (Amplifier and A/D converter).
- DAS (Data Aquisition System), in this case an Arduino that will send the data to a PC.

Although this is the most basic of configurations, it shows the more simple elements that a rocket stand will need in order to obtain the performance factors such as the specific impulse or the evolution of the thrust throughout time.

For bigger rockets, other inventors have developed bigger test stands that are more complex. For example Richard Nakka, an amateur creator, has built some very interesting models such as the STS-5000 [7]:

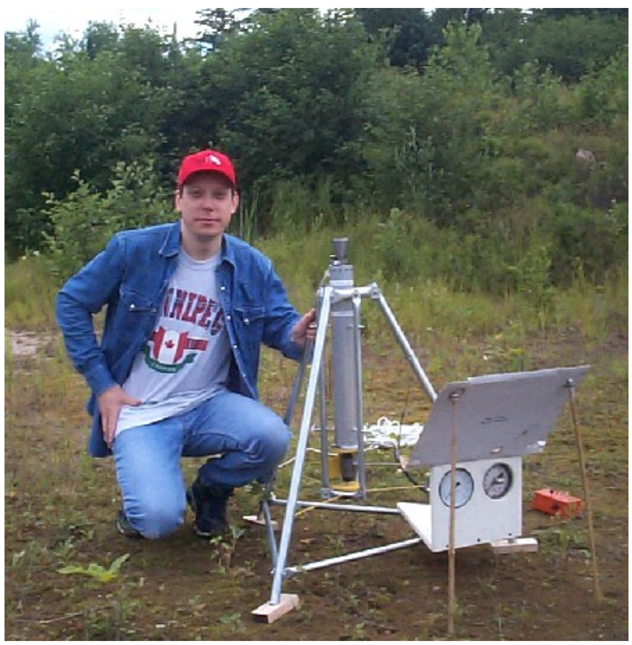


Figure 2.7: Richard Nakka's Statis Test Stand 5000. [7]

This is a vertical downwards oriented test stand for solid fuel rockets that has a capacity to test M-class or lower solid rocket motors with a thrust of up to 5000 Newtons. It is interesting to note that in order to test the structural viability of this test stand, it was hydraulically proof loaded to 105% of the design capacity (5300N). The advantage that this stand has compared to others is that as it is a tripod it is self-leveling on any ground which means that equal load distribution will be achieved at all legs and that it is foldable in order to be portable.

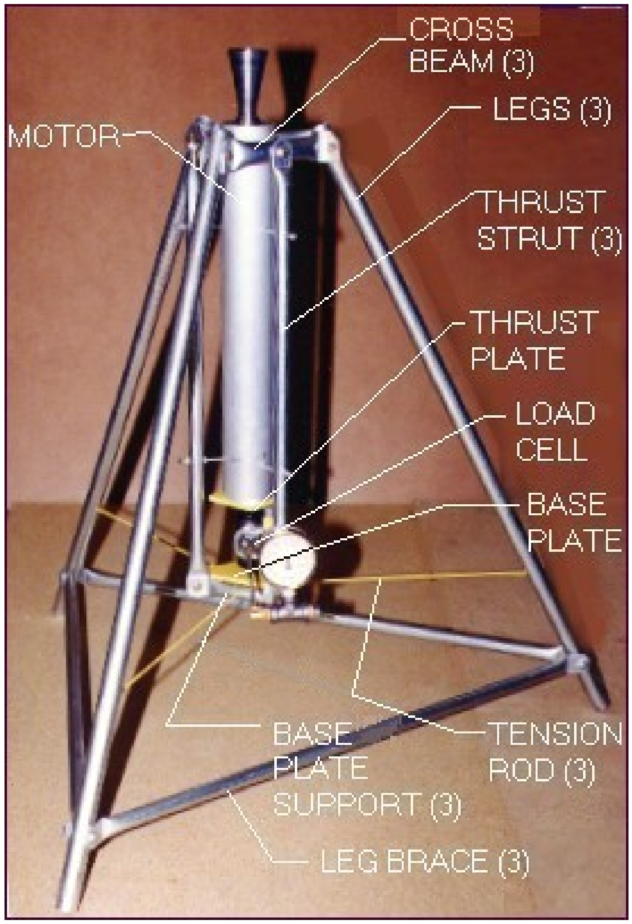


Figure 2.8: Richard Nakka's STS 5000 image illustrating the main components. [7]

This test stand was designed with simplicity in mind, using EMT (Electrical Metallic Tubing) as the main structural components. The bolted design allows for easy disassembling for transportation and storage reasons. Also the simplicity of construction allows for easy replacement and repairing of the structure in case that a catastrophic failure occurs.

Design of the test stand

In order to arrive to a suitable solution for our requirements, it is needed to study the different concepts and their advantages. In doing so, it will be judged the more suitable solution for our capacities. The different parameters to be analyzed in the design of a rocket test stand, before starting to develop it, are mainly the orientation of the bench and concept, the materials used in the construction, the electronics used and the methods of construction.

3.1 Conceptual Design

3.1.1 Motor orientation

There are 3 main types of rocket test stands when it comes to motor orientation. These are horizontal stands, vertical stands with the nozzle facing upwards and vertical stands with the nozzle facing downwards. Each of these orientations have their advantages and disadvantages. Nowadays the most used orientations are the horizontal for medium and big sized rockets and the vertical orientation with the nozzle facing downwards for big facilities, although as previously stated in the state-of-the-art, a vertical orientation with the nozzle facing upwards might prove useful for compact solutions.

1. Vertical orientation with the nozzle facing downwards

Figure 3.1: Test of the Mk IV rocket from the Boston University Rocket Propulsion Group (BURPG). [8]

(a) It is the most similar to a real scenario as the rocket will be flying upwards when launched.

(b) It is the more precise way of obtaining the performance of the motor, provided that the weight has been taken into account. As it is a vertical orientation, the weight of the rocket will have to be taken into account in order to obtain the total impulse generated by the motor, which for liquid-fueled engines would be easier as the weight of the fuel is not inside the combustion chamber as with solid fuels.

(c) Also, one of the main disadvantages of using this type of orientation is that as the thrust is projected upwards, which will mean that if the structure of the test stand is not properly fixed or weighted down with ballast or counterweights it could lift, tip to the side or move causing a catastrophic failure. This problem will mean that the overall structure of the test stand will need to weight more than other configurations.

2. <u>Vertical orientation with the nozzle facing upwards</u>

Figure 3.2: Vertical test stand with the nozzle facing upwards developed by Dewayne Doud in 2005. [9]

(a) This geometry has the main advantage in the thrust direction. The fact that the thrust will push the structure of the test stand towards the floor will mean that no counterweights or fixing structures will be needed.

(b) It is a geometry optimal for small lightweight portable solutions.

(c) It has the same problems with taking into account the weight of the rocket and fuel as in the previous case as it is a vertical orientation also.

(d) Although it makes the construction of the structure easier it has problems in regards to the accuracy of the thrust measurements and performance of the rocket motor. This problem is generated by the fact that the orientation of the rocket is 180 degrees opposite to what the rocket would be in a real case scenario.

(e) This might be reflected in the burning time and following thrust generated by the propellants as it is demonstrated in this paper [10]. It is proven that the burning time and evolution of the burning area is affected by the orientation of the rocket in respect to the gravity. Which means a difference in performance of the vertical position facing upwards compared to facing downwards, which will show a bigger time of burn and so less thrust generated.

Table 3.1: Experimental results obtained in [10].

Sl. No	**Vertical (Top to bottom burning) (mm/s)**	**Inverted (Bottom to top Burning) (mm/s)**	Horizontal burning (mm/s)
1	2.685	2.832	2.822
2	2.695	2.840	2.837
3	2.705	2.851	2.832
4	2.659	2.853	2.805
Average	**2.690**	**2.840**	**2.820**

It can be seen that the vertical disposition with the nozzle up top gives the biggest difference to the vertical nozzle down orientation.

3. Horizontal orientation

Figure 3.3: Horizontal test stand from Alexander Bruccoleri at Dartmouth College. [9]

(a) The horizontal orientation is one of the most used orientations as it gives relatively good measurements of the performance compared to the real vertical orientation but eliminates some of the problems present in a vertical orientation with the nozzle facing downwards.

(b) The horizontal orientation eliminates the necessity of taking into account the weight of the motor and the propellant and thus eliminates the component of the weight into the measurements of the produced thrust. It will also make it easier for calibration purposes.

(c) This orientation reduces the cost of construction and complex weighting parts compared to the vertical downwards geometry as it can be fixed to the floor or supported against a wall in order to fix it. This will reduce the overall weight and complexity of the structure and reduce the cost of materials.

(d) It must be noted that this orientation even though it eliminates factors when calculating the thrust produced, does not provide with the same actual performance as the actual attitude that the rocket would have in a launch scenario. Although it is notes in paper [10] that the relative performance of the motor in this orientation is closely similar to the vertical orientation. This difference can be caused by the difference in convection fluxes inside the motor as noted in paper [11] and also because of the difference in burning area in the grain surface as it can be observed in the following image:

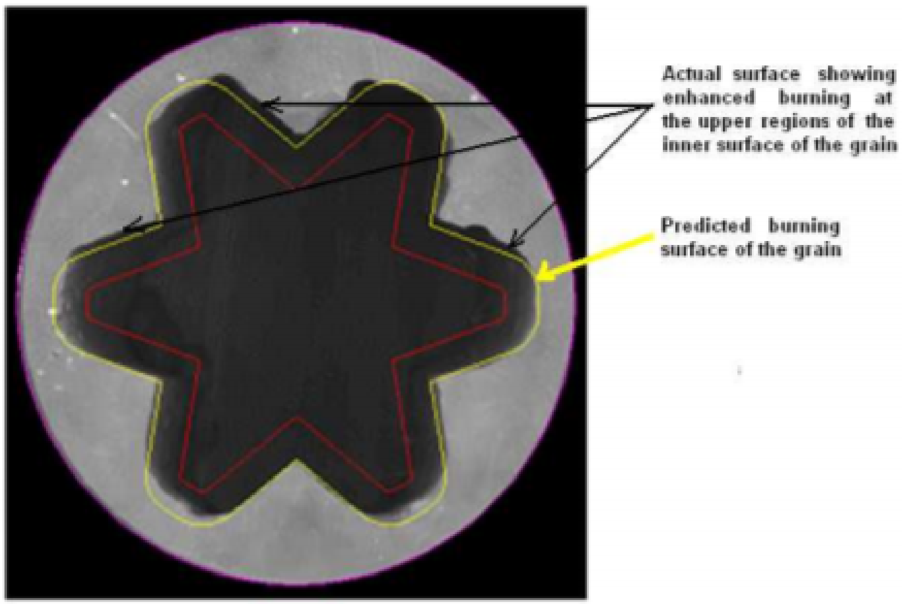


Figure 3.4: Photograph shows that the upper regions of the inner surface of the star grain is burning faster than the lower surface. From Aurora project [10].

It can be observed that after the 1 second burn the evolution of the grain burning area is not the same as expected and it is affected by the horizontal disposition of the rocket. It is deduced that the biggest erosion at the top and lower erosion at the bottom is caused by the effect of the orientation in the flame and convection fluxes inside the combustion chamber.

(e) For another part, slag accumulation and grain sedimentation in the nozzle is different in the cases of horizontal and vertically oriented rockets, as it can be seen in the paper [11] and in the following images:

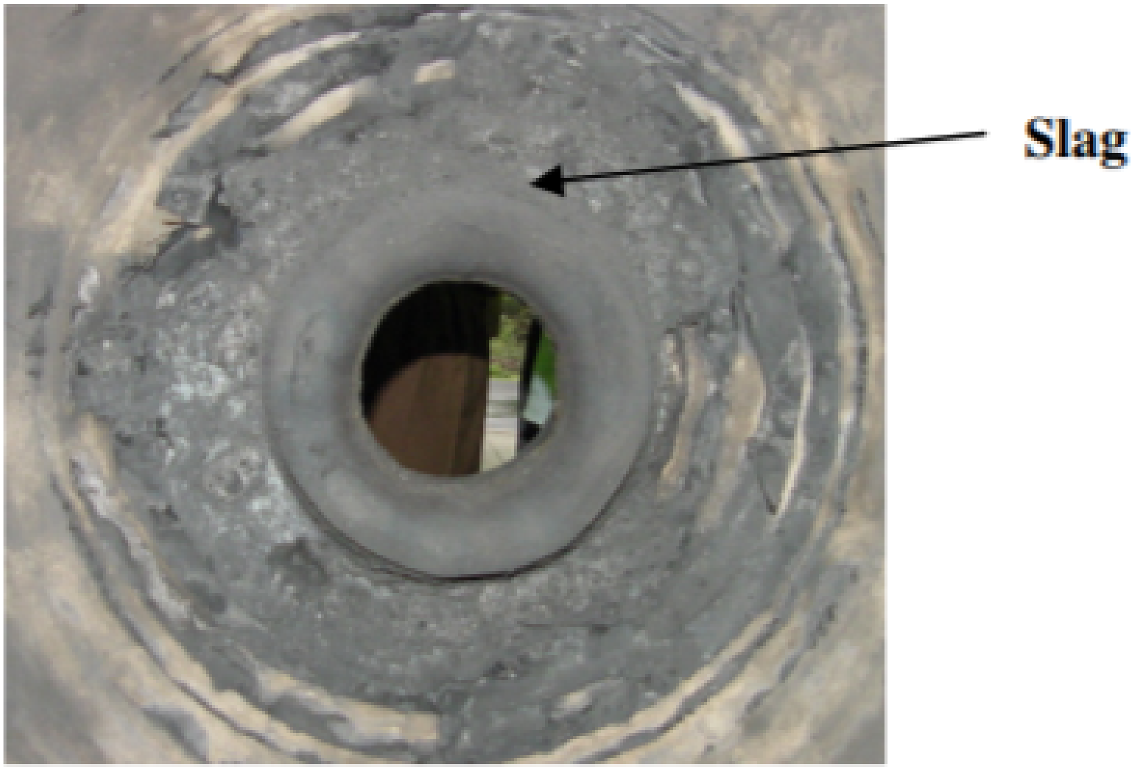


Figure 3.5: Slag accumulation in the nozzle area of a solid propellant motor in a horizontal configuration. [11]

It can be observed that some slag and results form the combustion of the propellant can become attached to the surrounding areas of the nozzle, specially for submerged nozzles, thereby reducing the performance.

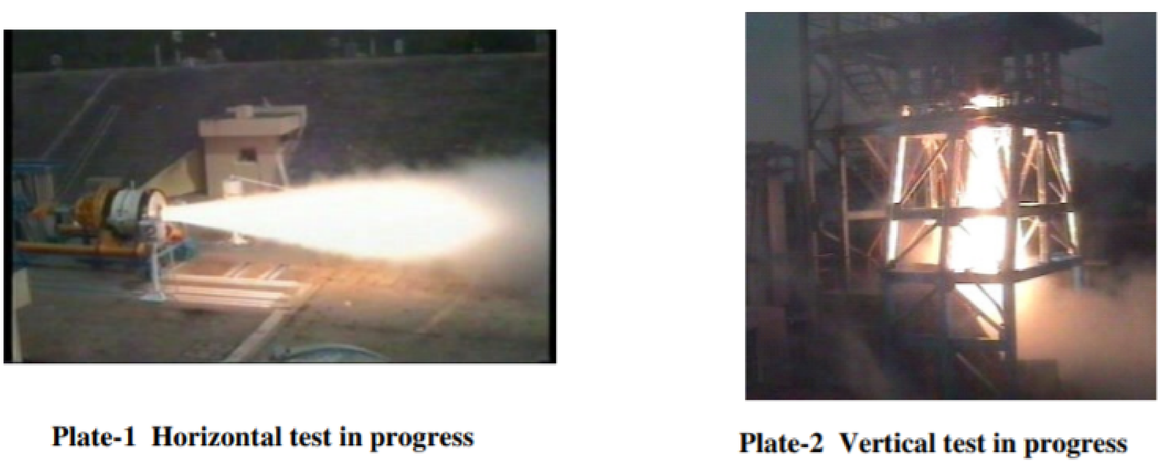


Figure 3.6: Different orientations of the tests performed. [11]

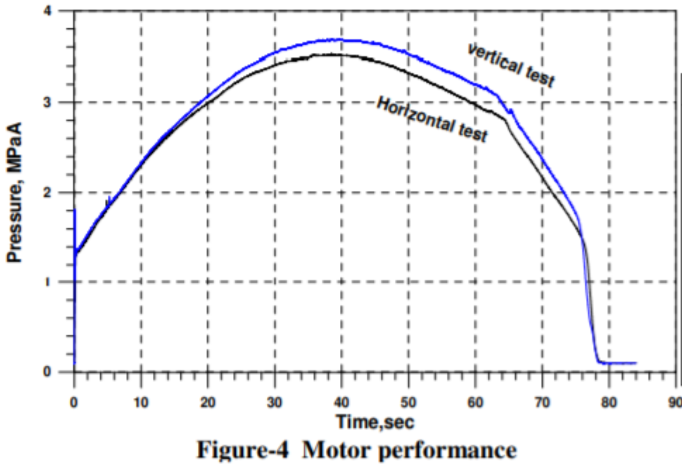


Table -3 Ballistic parameters

Parameters	Horizontal	Vertical
Burn Time(sec)	76.97	75.86
Action Time (sec)	77.74	77.64
Pmax, MPaA	3.53	3.68
Burn Time Pavg, (MPaA)	2.82	2.97
Action Time Pavg (MPaA)	2.8	2.93

Figure 3.7: Results obtained from the different orientations in the test performed in [11].

It can be observed the difference in pressure at the combustion chamber obtained for the same motor and same propellant, in a vertical and horizontal configurations. It can be observed that the results from paper [11] are in accord with what was obtained in paper [10] as the burning time of the vertical disposition is faster that the horizontal one indicating a bigger burning rate of the propellant.

3.2 Electronics

3.2.1 Objective

The objective of the electronics in this system will be of collecting the data generated during the test of the solid propellant motor. Without the electronics the bench should be able to be used autonomously and safely with a rocket motor. The function of the electronic system will be that of sensing and recording the thrust generated by the motor in the bench. For this reason it is needed the following conceptions:

- Sensing apparatus that accurately obtains measures from the applied force.
- Electronics to process and convert this analog signal into a digital stream of data to be used in a computer.
- Battery or power supply for all the electronics.
- Computer to analyze and post-process the generated data.

3.2.2 Electronics selection

The selection of the electronics is very important as it will decide the grade of accuracy and number of data generated in our design. It is also very important as cost is a parameter very dependant on it, depending on the resolution and accuracy desired by our necessities, the electronics' price can vary from under 100 euros to more than thousands of euros. This will also determine the range of motors that the stand will be able to test.

Load Cell

The main part and most important electronic piece of equipment in the bench is the sensing component, one could say it is the "heart" of the test stand. It will convert the load (thrust generated by the motor) into electrical signals to be processed later. It will determine the range of motors that the stand accepts and the accuracy with which the samples are taken.

There are different methods of obtaining the thrust force from a test stand, as seen in the state of the art the first techniques used in the beginnings of rocket history were more analog methods, constructed with springs, levers and analog dials. Later other methods were invented such as "thrustometers" and "thrustographs", which by means of a sled on rails plotted the thurst evolution on a moving piece of paper supplied by a feeding mechanism.

With the evolution of electronics and transducers, these more mechanical and archaic methods were stopped using and load cells became the mainly used method of measuring the thrust. In specific Strain Gauge Load Cells.

Strain Gauge load cells are capable of converting into an electrical signal the force applied into a surface, are small in size and cheap in cost. With the affordability of electronics, strain gauge load cells have become very accessible.

A strain gauge load cell is mostly a metallic structure that has one or more strain gauges on its body that deform as a force acts upon the structure. This deformation will lead to a deformation of the strain gauge, which in turn will modify the resistance value that the strain gauge presents to an electrical current. The change in output voltage will be proportional to the force applied, thus making it possible to determine the force value provided that the sensibility is known.

In the following figure, it can be observed that a single strain gauge is deformed when a compression or tensional load is applied into a load cell. This deformation will change the resistance of the gauge to the current passing thorough its wires as the wires of the gauge are made longer and thinner with the tensional stress or shorter and thicker with a compression of the cell.

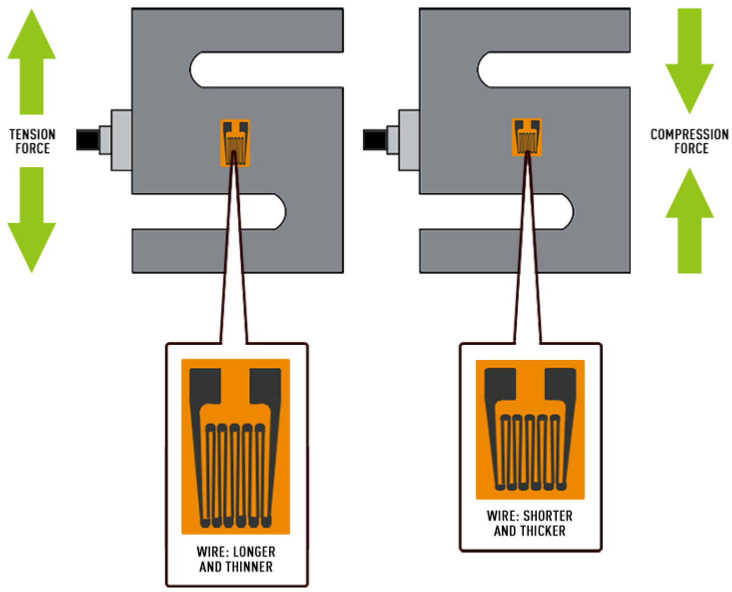


Figure 3.8: Deformation of a single strain gauge in a load cell. [12]

Because measuring the change in a single strain gauge is very difficult as the resistance change is very small, increasing the number of gauges applied in conjunction into a load cell allows to obtain a more measurable change. For this reason, a set of 4 gauges are applied in a Wheatstone Bridge circuit.

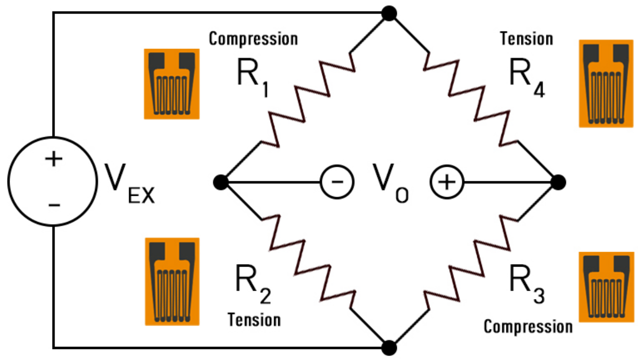


Figure 3.9: Wheatstone Bridge circuit. [12]

The basic operation of a Wheatstone circuit is to amplify and make visible a change into one or more of the resistances. Using Ohm's law, it is possible to determine the change in the output voltage in function of the resistances.

$$V_o = [R_3/(R_3+R_4) - R_2/(R_1+R_2)]V_{ex}$$

Where V_o is the output voltage, R1 to R4 are the resistance of the four strain gauges and V_{ex} is the excitation voltage that will be of known value.

YZC - 526

The chosen load cell for this test stand has been the YZC-526, which is an s-type load cell with a maximum load capacity of 1 ton (9810 N). It has been chosen this one for its inexpensiveness and high load capacity.

Figure 3.10: YZC-526 Load Cell. [13]

It can be observed in the YZC-526 load cell the different wires coming out of it and how they correspond to the inputs and outputs of the Wheatstone bridge. It can be observed that there are 4 wires connected to the cell, they are: white, red, green and black.

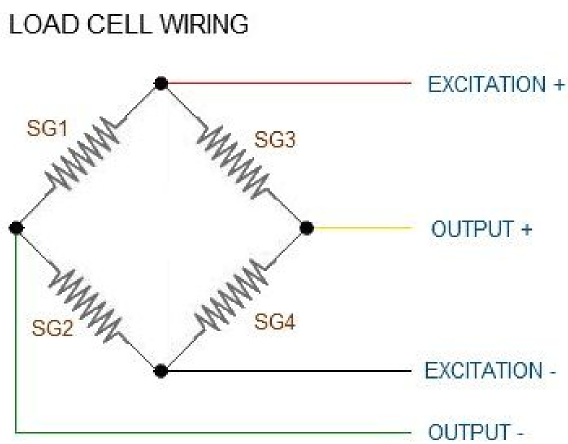


Figure 3.11: Wheatstone Bridge circuit wire diagram. [14]

Table 3.2: Wire color-coding

Wheatstone bridge node	Typical color code
V_{ex} (+)	red
V_{ex} (-) or GND	black
V_o (+)	white
V_o (-)	green

With that in mind, the connection between the laod cell and the other components can be deducted easily:

Table 3.3: Wire connections of the load cell component.

Load cell output color of the cable	Input port
V_{ex} (+) - red	5V supply on Arduino Mega
V_{ex} (-) or GND - black	Ground pin on Arduino Mega
V_o (+) - white	Analog input on the DAAU shield (+)
V_o (-) - green	Analog input on the DAAU shield (-)

The YZC-526 load cell has the following main characteristics [13]:

Table 3.4: Specifications

Parameter	Value
Manufacturer	Guang CE
Model	YZC-526
Load cell material	Alloy steel
Maximum load capacity	1000 kg
Sensitivity	2 +/- 0.05 mV/V
Combined error (%RO)	< +/- 0.030
Creep (%RO/30 min)	0.02
Temperature effect on sensitivity (%RO/°C)	0.0016
Recommended excitation voltage	10-15 V

Amplifier

Once the load cell is setup it is needed to amplify the signal that will be generated in the order of mV to a suitable magnitude to be used.

If the 5V output from Arduino is used as the excitation voltage for the load cell, which has a sensitivity of 2mv/V, then the complete range of voltage output would be of 10mV. Which is too small to be used for an Arduino without amplifying it first.

For this reason it has been chosen the following amplifier board: the Differential Amplifier shield for Arduino Uno (DAAU) from Upsilon Engineering.

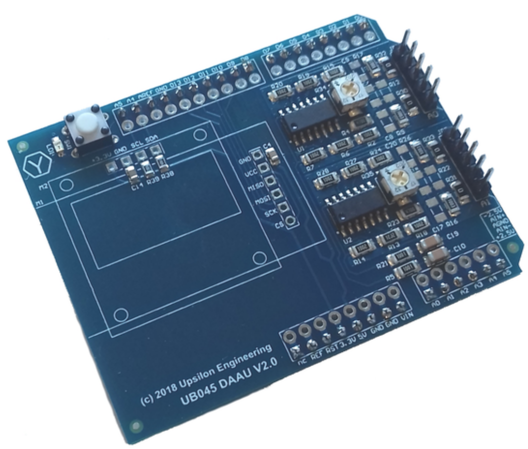


Figure 3.12: Upsilon's DAAU amplifier. [15]

This amplifier has a 2 channels and each has a gain k than can be set from 9 to 43. Thus the 10 mV would become a difference in 430 mV which can be used by the ADC.

A basic example of the operation of this amplifier is presented in the following scheme:

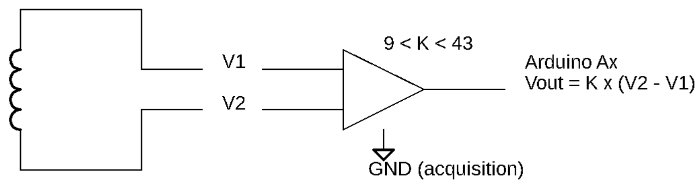


Figure 3.13: Basic example with an inductive sensor. [15]

In order to adjust the gain, an on-board potentiometer can be trimmed. Also, the amplifier uses analogs inputs A1 and A0 to acquire two separated differential signals, although in this case only one will be used.

In the following image the pinout of the shield can be observed:

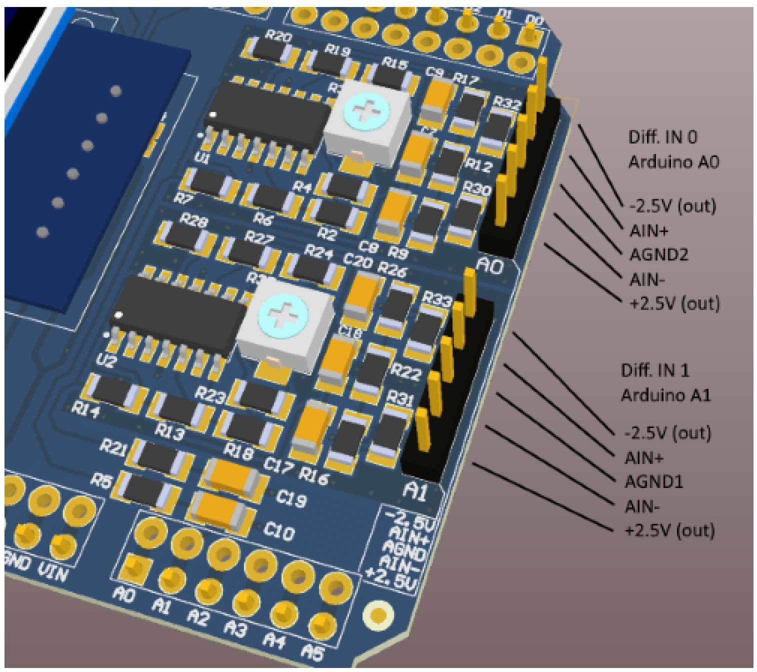


Figure 3.14: Pin connections on the amplifier. [15]

As it is built as a shield, it can be mounted on top of the Arduino Mega without the use of cables or other components.

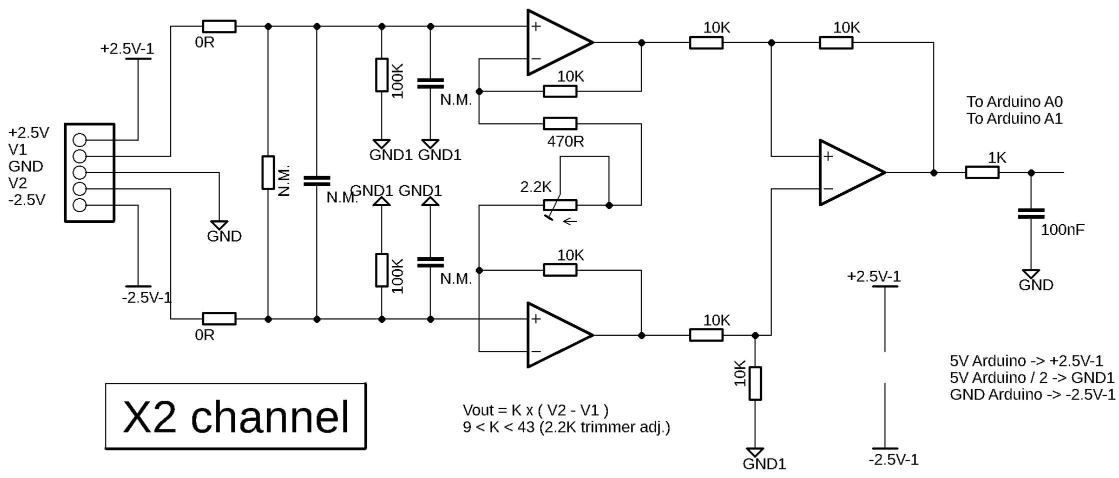


Figure 3.15: Schematics of the internal components of the amplifier. [15]

The selection criteria for this amplifier was primarily based on availability and arduino compatibility as there are not many amplifiers for this type of operation as usually these type of systems come together with the load cell and the data acquisition in conjunction. For this reason not many alternatives where found to be bought for a moderate price separately.

Another alternative that was contemplated was to use a INA125 amplifier in a breadboard or integrated circuit, but the realisation of such a project would be far more complicated than to use the DAAU found, which has the ability to be integrated seamlessly into an Arduino Uno o Mega.

Analog to Digital converter.

Figure 3.16: ADC ad7606. [16]

Once the signal is amplified it still needs to be translated into a digital signal so that Arduino can process it. An analog-to-digital converter will translate the voltage of an electric current into a digital number that will be proportional to that voltage. For example in a 3 bit ADC converter there are $2^3 = 8$ levels, so a singal with a range from 0 V to 1 V, will have a voltage resolution of $1V/8 = 0.125V$. For this reason, it is very important on an ADC the resolution in number of bits.

The second most important parameter to take into account for an ADC converter to be used in a test stand is the Sampling Rate. This parameter indicates the number of samples that the converter is able to process per second, so if the sampling rate is high the more samples that will be measured in a second and the more precise that the measurement of the thrust vs the time will be. Thus, creating a smooth graph without big discrete steps.

The chosen converter has been the AD7606 because of a good performance in resolution and sampling rate, which are above those in the requirements.

It is an ADC capable of receiving 8 different analog signals, with a 16 bit resolution ($2^{16} = 65536$ levels) and a sampling rate of 200 ksps.

This means that the minimum value detected will be of:
$5/2^{16} = 0.0763$ mV
Which is far lesser than the amplified signal from the differential amplifier.

Table 3.5: Technical Specifications of the AD7606. [26]

Parameter	**Value**
Operating Voltage	3.3 or 5 Vcc
Protocol	SPI
Number of channels	8
Resolution	16 bit
Sampling Rate	200 kSPS

The selection criteria to chosing this ADC instead of other was a combination of availability to be purchased on the web, performance adequate to that in the requirements as the 200 kSPS is high enough to have enough samples in time to obtain a good enough plot of the thrust vs time, the 16 bit resolution which will make precise enough measurements to plot, the low price and the arduino compatibility.

Other candidates and possibilities where studied, as the use of the ADS1115 or the HX711 or more expensive DAQ systems.

Table 3.6: Technical Specifications comparison. [26] [27] [28]

Parameter	AD7606	HX711	ADS1115
Number of channels	8	2	4
Resolution	16 bit	24 bit	16 bit
Sampling Rate	**200 kSPS**	80 SPS	860 SPS

As it can be observed the only performance that fulfills the requirements between these candidates is the one selected. Other suitable options (not included in the table) involved a higher price.

Arduino Mega

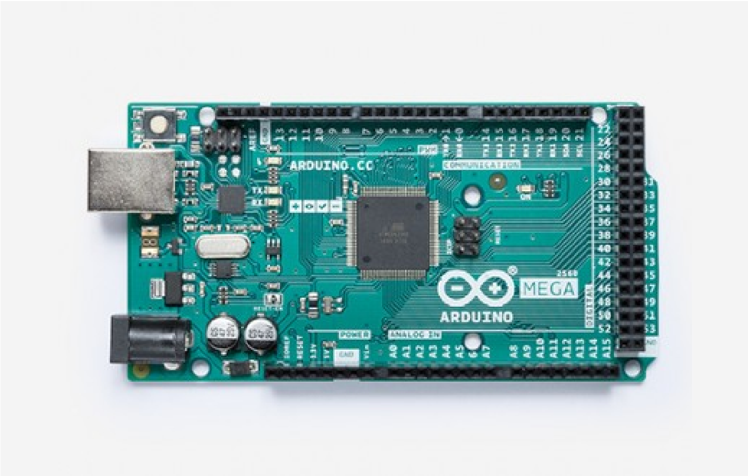


Figure 3.17: Arduino Mega Rev.3. [17]

Once the signal has been processed into a digital form, then it can be used by a micro-controller for storing the data, processing the data or taking any actions. In this case the data obtained is only received by the Arduino and then sent to the computer for plotting.

The chosen solution was at first the Arduino Uno, which is the basic Arduino model, an inexpessive one, that is provided with an ATmega328P micro-controller. It was chosen instead of other Arduino as it was compatible with the amplifier DAAU shield. Later it was found that when combined with the shield more ports where needed in order to connect it with the ADC converter at the same time, so another solution had to be found. This other solution was the Arduino Mega, and provided with a better micro-controller, the ATmega2560, and more pins, was suitable for all the connections that were needed.

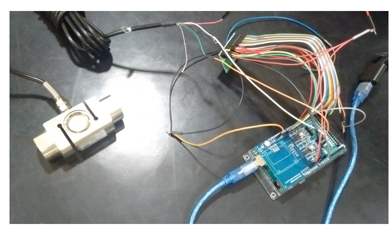
Table 3.7: Technical comparison between Arduino models. [17] [29]

Parameter	Arduino Uno	Arduino Mega	Arduino Micro
Price	14-25 €	16-35 €	12-18 €
Dimensions	68 x 53 mm	101 x 53 mm	48 x 18 mm
Micro-controller	ATmega328P	ATmega2560	ATmega32U4
Clock Speed	16 MHz	16 MHz	16 MHz
Flash memory	32 KB	256 KB	32 KB
Voltage Level	5V	5V	5V
Digital I/O Pins	14	**54**	20
Analog pins	6	**16**	12
USB Connectivity	Standard A/B USB	Standard A/B USB	Micro-USB
Shield Compatibility	YES	**YES**	NO

Comparison of the chosen solution to other options

The chosen solution for the electronics that has been presented before was not the only one possible option, it was after the characteristics of eahc option were analyzed that it was found to be the best option. In this chapter it is discussed the reason why it was found to be the most adequate solution and it is shown the different alternatives present in the market for the electronics.

Table 3.8: Technical comparison between different solutions for the electronics module.

Model	Key parameters	Price	Image
Developed solution: YZC-526 load cell + Arduino Mega + DAAU amplifier + ADC ad7606	Load Cell: Maximum capacity: 1T, Sensitivity: 2mV/V. DAAU: Gain: 9-43. ADC: 8 channels, 16 bit resolution, Sampling rate: 200 kSPS.	35 + 25 + 25 + 36 = **121** €	
Omega products: Load Cell LC103B and signal conditioner TXDIN1600 [33] [34]	Load cell capacity: 9072 kg. Sensitivity: 3+/-0.008 mV/V. Excitation voltage for the signal conditioner: 5V. Range from -38 to 38 mV. Sampling rate from 10 to **80** SPS.	188 + 173 = **361** €	 

DATAQ Model DI-718B-U (without load cell) [35]	Low-Cost, Portable, USB Data Acquisition System. 8 channels. 14 bit ADC conversion. 4800 Hz Sample Throughput Rate.	**536 €**	
Monodaq-U-X (without load cell) [36]	50 kS/s, 16 bit analog voltage input (+-10 V) strain gauge amplifier. 8-channel multiplexed analog voltage input.	**299 €**	

It can be observed that the price on a commercially available pre-made solution from one of these companies is on another price range above that of a solution developed in-house. Also it can be seen that some of the pre-made solutions have worse characteristics than the one developed, as a lower sampling rate (80 SPS on the Omega solution) or a lesser load capacity (9072 kgf on the Omega solution).
Other solutions did not provide with a load cell, only the data acquisition unit, which would led to another expense on the cell.

For these reasons it was chosen to develop the electronics module with an Arduino platform and modules, instead of buying an already made product.

Testing and results

Once all the components have been selected and they are connected from the load cell which receives the thrust force as a strain on the gauge, to the computer which is able to process the signal, a simple test was done to guarantee that all the part functioned.

The test consisted of applying a force on the cell with different weight above it or by applying pressure with the hand, and observing the change and recording of the data on the computer.

It was observed that the load cell without a load returned to zero and that applying a variable load on the cell the recorded values varied also.

The connection of all the parts and the whole system hooked up can be observed in the following image:

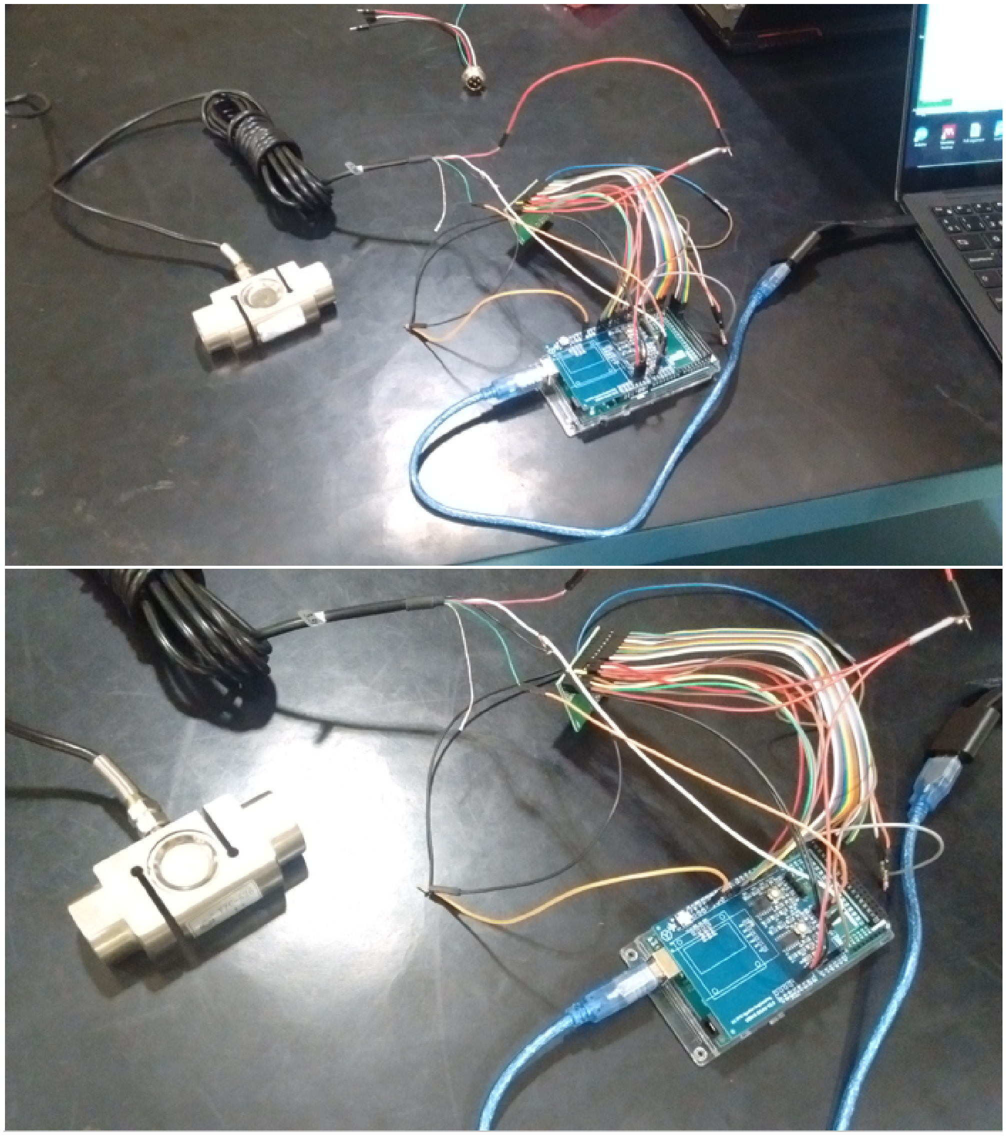


Figure 3.18: Test of the electronics.

3.3 Firsts designs

After reviewing the current state of the art and all the requirements and conditions that the test stand was supposed to comply with, it was first studied different designs before it was arrived to a design suitable for construction and use.

3.3.1 First design

The first concept that was at first thought was that of a vertical test stand with the nozzle looking downwards, as to simulate as closely as possible to reality the performance of a rocket. In this case the rocket would have the same orientation as in the launch thus giving the more accurate measurements.

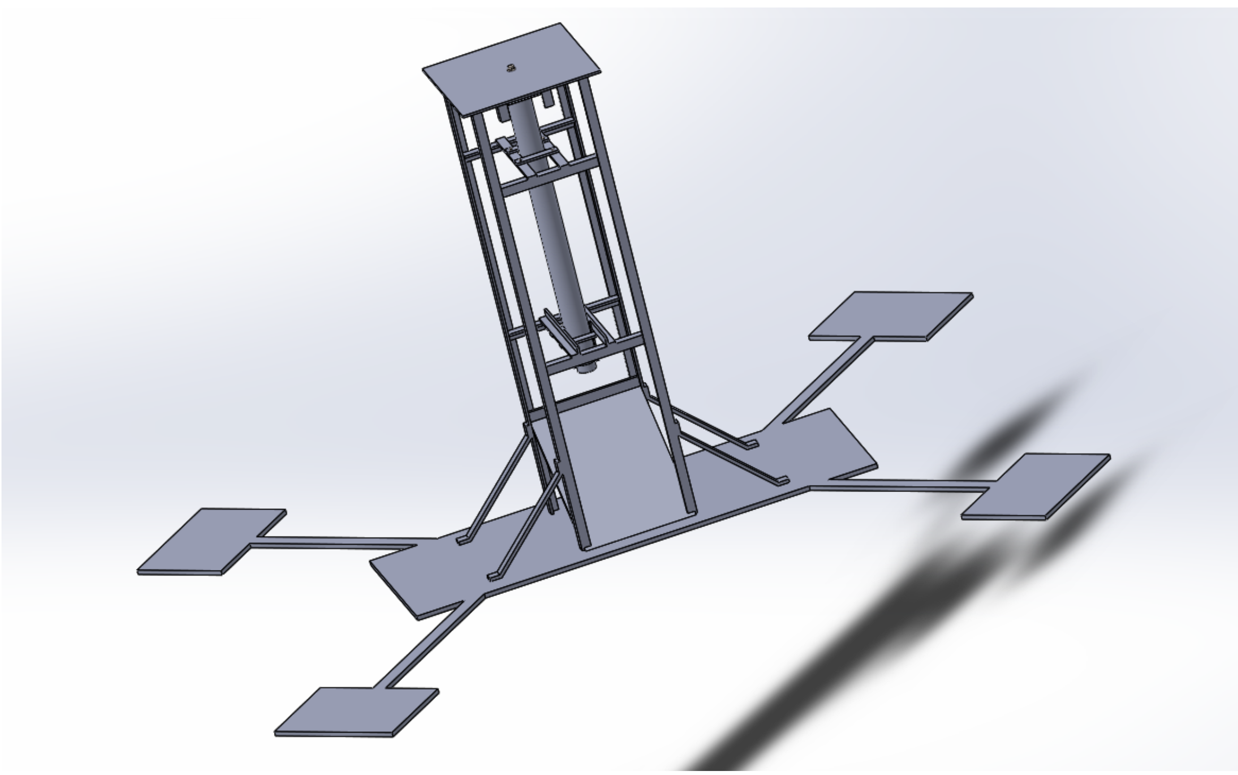


Figure 3.19: Design number 1

This design had the load cell mounted on the top plate, which would present problems if the electronics had to be mounted at the top of the stand as they would be hard to access once the stand was on an upright position. Also it had 4 arms with a tray at the end of each arm with the purpose of containing weight that would counteract the thrust generated by the engine. Also the arms would stabilize the structure in case that the thrust tilted the stand towards any side if the force was not totally vertical in respect to the ground. Furthermore, It was provided with a deflection plate in order to direct the plume towards a safe zone.

The guiding of the motor and fixing in an axis was supposed to be done by a set of six guides (one set on top and one at the bottom) that would be screwed into the vertical rails and unscrewed depending on the length of the motor. This way the bench could be used for many different types of motors. Also the separation between the guides could be changed by the same method. These guides were L shaped beams that fixed the motor without pressing upon it, thus leaving the motor free to move on a vertical axis in order to not modify the measurement of the force produced on the top plate.

The dimensions of this design had to be large as the requirements stated that a rocket motor with a diameter of at maximum 150 mm had to be able to be mounted. For this reason, the stand had a size of 2 meters high and 4 meters wide. Which made it very large, difficult to build, difficult to disassemble and transport and very heavy. For this reasons the vertical orientation concept was withdrawn and other geometries were started to be thought, in concise the horizontal orientation.

The motor used for this 3D model had the dimensions of the biggest motor available to be bought on the internet from Aerotech, with a thrust of less than the capacity of the load cell and a diameter of less than 150 mm. This motor was the RMS-98 High Power Motor [18].

Figure 3.20: Image from the Aerotech catalogue. [18]

3.3.2 Second design

The second design was thought from the concept of having a horizontal orientation, this would solve the problems of too big dimensions, complexity of the design and transportation.

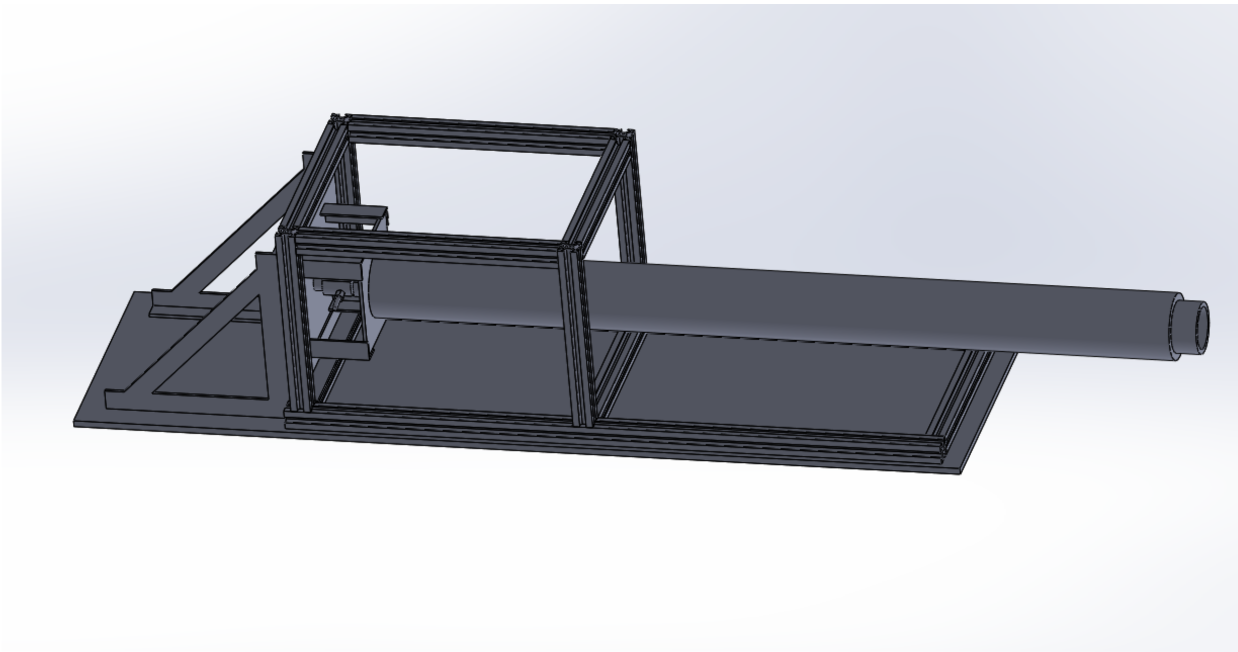


Figure 3.21: Design number 2

It can be observed that even though this design was not finished, as a problem was found, it was already looking smaller and more simple than the first design. This allowed the structure to be able to be more easily transported in a car or van, and a more simple method of construction.

In order to find a more easy to build approach and flexible in order to mount and move the pieces to accommodate the rocket motor and in order to disassemble and rebuild it on the field, it was thought of having beams with a T-slot profile. This profile can be seen in the following image and is a very good option for flexible frames that can be changed on-the-go offering flexible solutions.

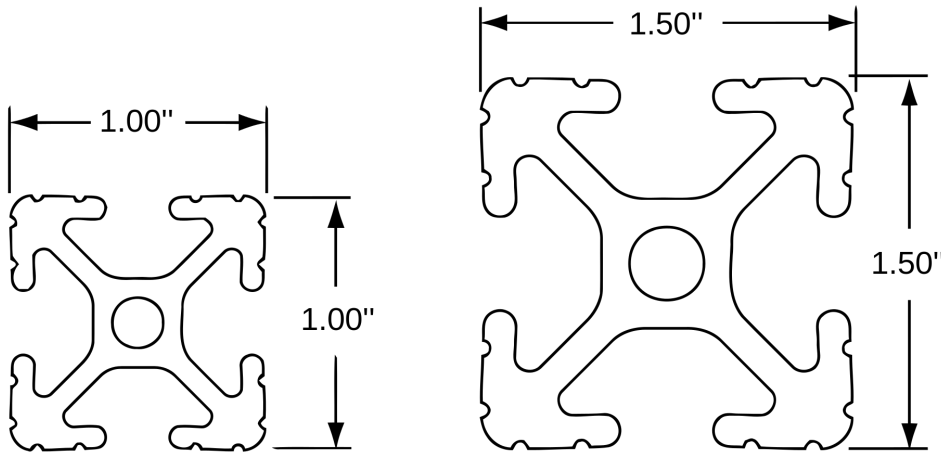


Figure 3.22: T-slot examples, series 10 and 15. [19]

This types of frames are mostly used in benches that require a flexible geometry such as for 3D printing or CNC machining.

This design was not finished, as it can be seen that it lacks a right hand support for the rocket motor, as this types of beams were not available for construction and it was opted for another more available and affordable type of frames.

3.4 Final Design

The final design was conceived from the idea of creating a horizontally oriented test stand with materials available from steel companies in the market that would allow to create a bench prepared to hold the biggest of amateur rocket motors (category N motors) available in the market.

With that in mind this stand was created, which is a middle sized test stand with a horizontal longitude of 1.6 meters, made from structural carbon steel. It is chosen to be constructed from beams and plates readily available and easily found in the steel market.

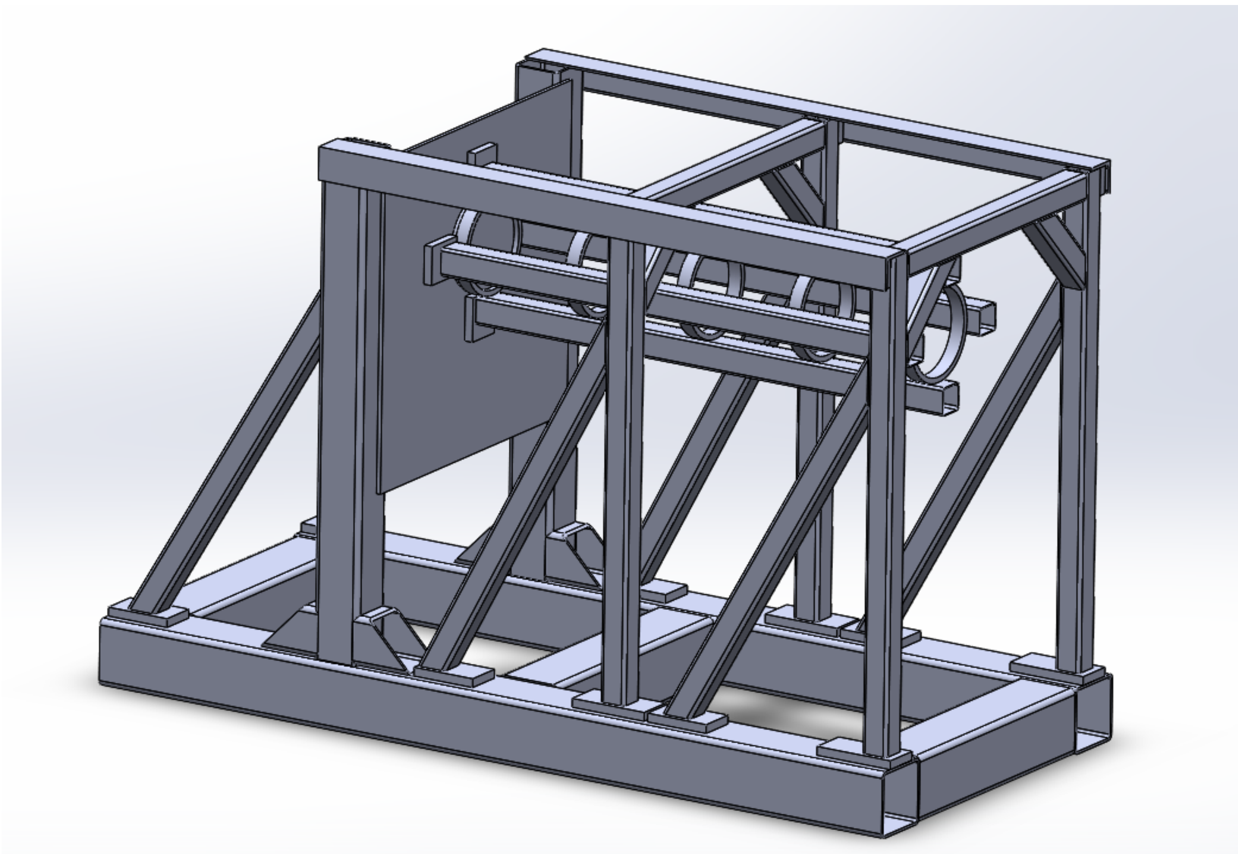


Figure 3.23: Final Structure 3d model.

It can be observed that it has a bottom rectangular frame composed of square shaped beams with a 120 mm size. There are two beams at each side and 3 beams connecting the sides and middle. These beams are welded together and are 120x120x5 mm of dimension.

Then there are 2 main beams that support the plate on which the thrust is acted upon that are 90x90x5 mm square profile beams. These two big beams support a square plate of 8 mm in width onto which the supports for the rocket motor are fixated. Thus the rocket motor will cause a force that will push the center of the plate, which will create a bending moment on the square beams.

The 2 main vertical beams are supported on top by a beam with an equal L profile with the dimensions of 60x60x6 mm, that joins the main vertical beams with two layers of supportive beams. The supportive beams that help the two main vertical beams support the load of the thrust are composed by square shaped beams with the dimensions of 50x50x2 mm. It can be observed that the incorporation of diagonal beams throughout the structure will help to transmit the load to the bottom frame by acting as diagonal braces. Also note that there are diagonal braces on the corners of the rectangular structures to give the frame better resistance to side stresses. Some gussets have been added at the bottom of the main vertical beams in order to give it a better resistance to bending moments. These gussets are welded to the main vertical beams but the gussets have a bottom plate which joins the beams to the bottom frame.

The vertical beams are joint to the bottom frame by the means of bolted plates (although in the figure the bolts are not modelled) that can be unscrewed in case that the structure needs to be dismounted for transportation.

Then there is the rocket motor mounting structure, it is a structure composed by four long square beams that support four equal rings and a circular plate at the bottom. The circular plate is where the motor end pushes towards, it is a flat plate that will transmit the load to the load cell which will reside between this circular plate and the rectangular plate from the frame. The four rings serve to hold the motor in horizontal position and have adjustable screws to adjust the diameter to any rocket diameter up to 180 mm, which is bigger that N category rocket motors.

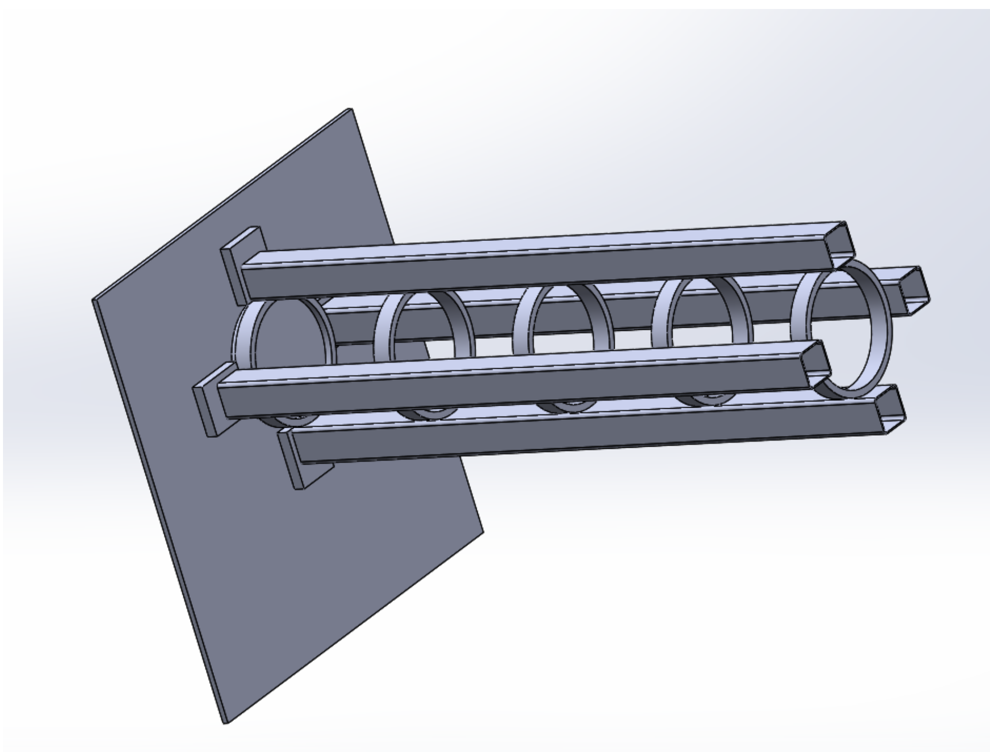


Figure 3.24: Rocket Motor holder 3d model.

It must be noted that the screws and holes are not portrayed in the model. Also the rocket motor which should enter on the center is not present.

Safety plate

In order to make the operation of this test stand safer it is necessary to create a safety plate that will cover the motor and stop any fragments or loose parts that were to come loose and be shot from the motor ignition or in case of a fatal failure and explosion. This safety plate will be perforated to allow sight of the rocket but will not have holes of diameter higher than any of the pieces that could present a danger to the personal. This shield will be made of steel.

3.4.1 Material

The materials used in the building of the structure are basically beams with different profiles and plates cut into different shapes and sizes. The following table reflects all the parts used in the creation of this structure:

Table 3.9: Materials used in the structure.

Component	Quantity	Longitude [mm]
Beams		
Square beam 120x120x5	2	1600
Square beam 120x120x5	3	500
Square beam 120x120x5	6	130
Square beam 90x90x5	2	916
Square beam 50x50x2	4	955
Square beam 50x50x2	10	900
Square beam 50x50x2	2	570
Square beam 50x50x2	4	230
L beam 60x60x6	2	1160
Plates and others		
Rectangular plates 70x150x16	8	
Rectangular plate 600x600x8	1	
Circular plate D180x35	1	
Circular rings D180x10x26	4	
Hexagon head bolts A2-70	52	

Figure 3.25: Examples of beam profiles. Extracted from [20].

The material these beams are made of is in all the plates and beams the same: structural carbon steel s235.

From the legal regulations regarding the Structural Safety on using Steel, from the Technical Code of Edification DB SE-A [37], it is known that steels on the actual nomenclature are classified in regards to their elastic limit. The elastic limit or yield stress, is the maximum stress that a material can resist while maintaining an elastic behaviour, if the load is increased on the material, the stress will be above that limit and the material will show a plastic behaviour where it can not return to its initial state.

The designation of the elastic limit on steels is shown as an S followed by the number of the limit.
$SXXX$

The used steel in all of the structure is **S235** steel and its properties are the following:

Table 3.10: S235 Steel Properties.

Parameter	Value
Yield strength (f_y)	235 N/mm^2
Ultimate strength (f_u)	350 N/mm^2
Elastic modulus (E)	210.000 N/mm^2
Shear modulus (G)	81.000 N/mm^2
Poisson coefficient (ν)	0.3
Thermal dilatation coefficient (α)	$1{,}2 \cdot 10^-5(\circ C)^-1$
Density (ρ)	7.850 kg/m^3

The main reason this material was chosen instead of other alternatives like composite materials or other alloys or metals like aluminium, was its availability in the market. There are many shops that can provide you with many different extruded, laminated or otherwise profiles and beams. The good performance shown by this steel in structural applications and the fact that is a material very used and tested is also a determining factor. On another hand, the weight was not an issue, so the high weight of the steel compared to other lighter alternatives was not an important factor.

3.4.2 Construction

Figure 3.26: Beginning of the construction process. Building of the base.

The main method of construction of this structure has been that of cutting and welding the different beams together, also bolt holes have been drilled in order to create separable pieces. For this reason the beams and parts of this structure are mainly bonded together by a combination of welding and bolts.

The machines used to build the structure have been mainly a rutile welder of 2.5 mm and a band saw to cut the beams.

First it was built the base by welding the different beams and cutting the small portions of 120x120x5 beam that will act as a reinforcement in the nodes of the main vertical 90x90x5 beams.

Then it was added the top beams, diagonal braces and the load plate.

Figure 3.27: Construction process, building of the top.

Once the primary structure was created it was needed to mount together and add the motor holding structure into the frame. The motor holding structure is referring to the four beams attached with circular rings and a circular end plate where the motor will be subjected and hold into position. This structure will be fixed by bolts into the load plate as shown:

Figure 3.28: Rocket motor holding structure.

And once everything was in its place, welded and bolted, the resulting finished structure was obtained:

Figure 3.29: Finished result.

Figure 3.30: Finished result with the rocket mounted.

Computer Aided Numerical Simulation

4.1 Objective

In this chapter it will be analyzed the designed structure in simulated conditions with the use of computer aided numerical methods, specifically the Finite Element Method (FEM). The software used to perform these analysis is the same as the one used to create the 3D model, which is Solidworks by Dassault Systemes.

The objectives of the analysis will be:

1. Static analysis of the structure to see if the material does not exceed the elastic limit at any point.
2. Buckling analysis to see that any of the beams does not buckle under a compression load.

In order to do the simulation in a laptop and in a practical time, some computational and physical simplifications have been made to the model to reduce the complexity of the problem. These simplifications and hypothesis have an impact on the results but the difference in the results is not big enough to justify the increase in computational time that would be needed for a more complex model with a more precise mesh for example. The different assumptions and simplifications that have been made are the following:

- The 3D model has been cleaned of all the complex geometries that does not impact the stresses distribution and some simplifications of the model geometry have been made, for example the small plates used in the bonding of the vertical beams with the horizontal base frame have been deleted as they would increase the model complexity. The erasing of these plates is not significant as without the plates the cross section is smaller thus increasing the stresses on that area. For this reason not taking them into account should leave a more restrictive model than with them modeled, thus it is a conservative approach. Other similar complex geometries have been eliminated for the same reasons.

- The FEA method used in SW for the beams has been simplified and the mesh of these beams parts is made with less control elements. In order for a part to be treated as a beam it is needed that it complies with the rule of having the ratio of length over the largest orthogonal cross-sectional distance from the centroid less than **3**, see reference [38]. If it does not comply then it must be considered as a solid and a more precise mesh and general model be applied.

4.2 Finite Element Analysis

The model that has been created in order to test the structural integrity of the test stand has been the following, it can be appreciated that some of the geometry has been simplified for meshing and computational time reasons.

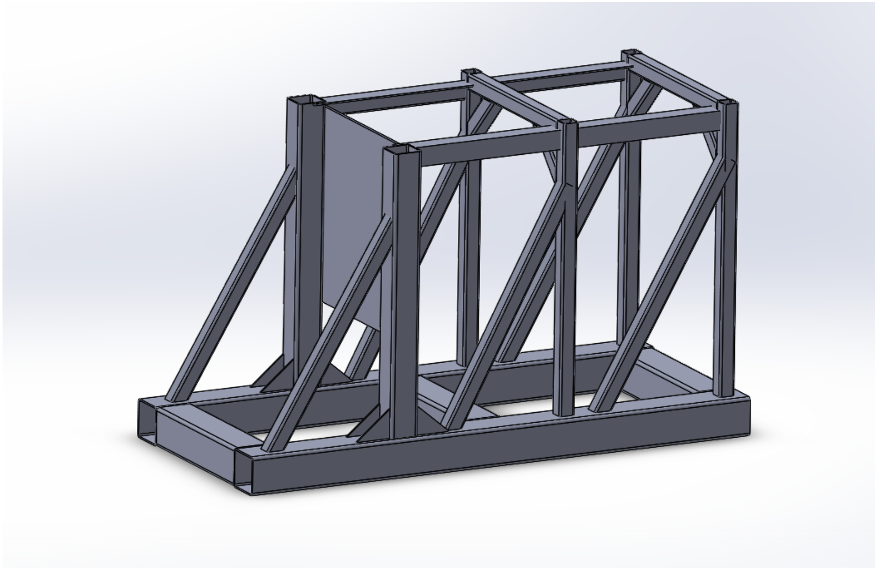


Figure 4.1: Simplified geometry model.

The rocket mount structure has not been included as the thrust of the rocket will be projected into the circular plate with 25 mm thickness that is bonded to the rectangular sheet of 1cm of thickness. It can be observed in the following image how the thrust force is applied to this area in particular.

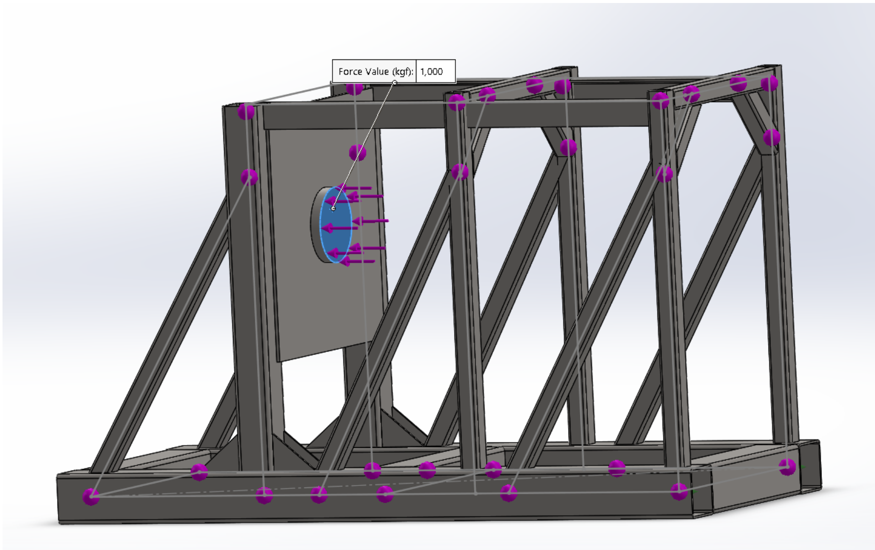


Figure 4.2: Load applied of 1000 kgf.

The value of the chosen force has been the more restrictive one, which corresponds to the load cell capacity of 1T of kgf. If the load were to surpass the 1000 kgf limit the load cell would break, for this reason, even though the thrust of the motor at any time should reach levels closer to 1000 kgf, it has been set this load to test the maximum capacity of the test stand in this configuration in the most extreme scenario.

It is known that the thrust generated by a rocket motor is dependant of time, so the maximum thrust has been taken into account. If it is observed the thrust evolution graph of the highest peaking motor in the Aerotech catalogue [18], it can be observed that it is still lower than the load of 1000 kgf. It can be observed in the following figure the evolution of thrust vs time of the motor that generates the biggest thrust [21]:

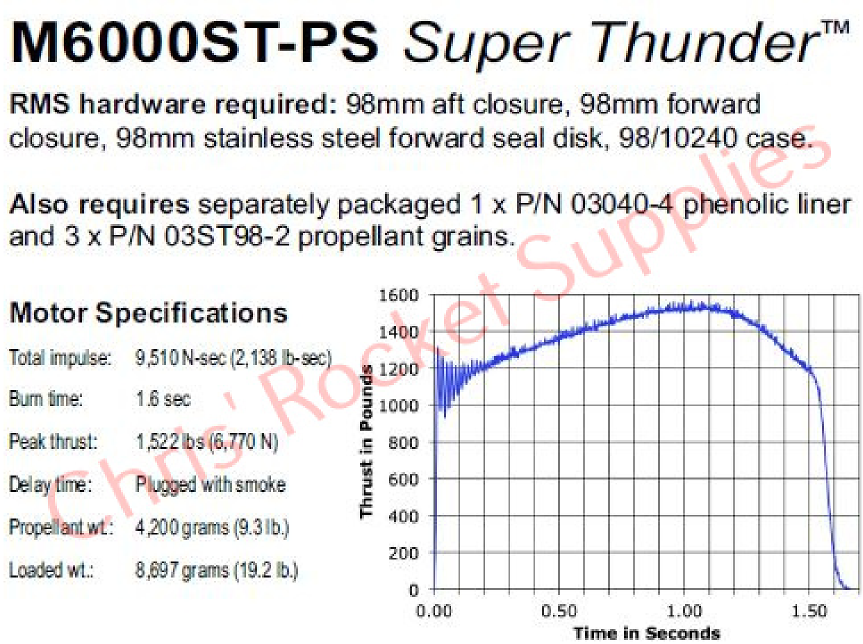


Figure 4.3: Thrust vs time and parapeters of the M6000ST motor. [21]

It can be seen that the peak force generated is of 6770N which the developed test stand would be capable of supporting.

Once the loads and restraints on the geometry have been defined, it is necessary to create a mesh that will give good results. For this reasons it has been developed an iterative procedure where different sizes of elements have been tested and this mesh has been found to give good results that do not differ almost from a mesh with a bigger resolution and more control elements. The generated mesh can be seen in the following figure:

- Type of mesh: standard (Voronoi-Delaunay meshing scheme).
- Global size: 18,953 mm.
- Tolerance: 0,948 mm.

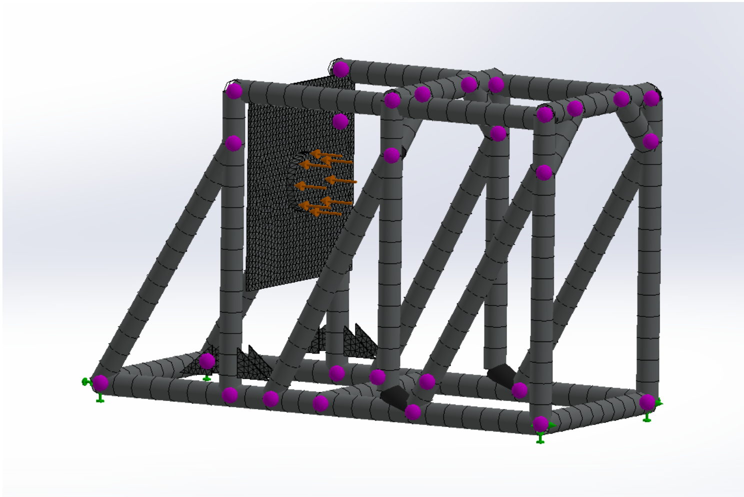


Figure 4.4: Mesh generated.

Once the mesh, load, material and fixtures are defined the simulation can be run. The results of the simulation are discussed as follows.

4.2.1 Static analysis

Here it is presented the Von Misses stress plot on the vertical plates that supports the load. The beams are not present in this plot as they are treated separately from the solids.

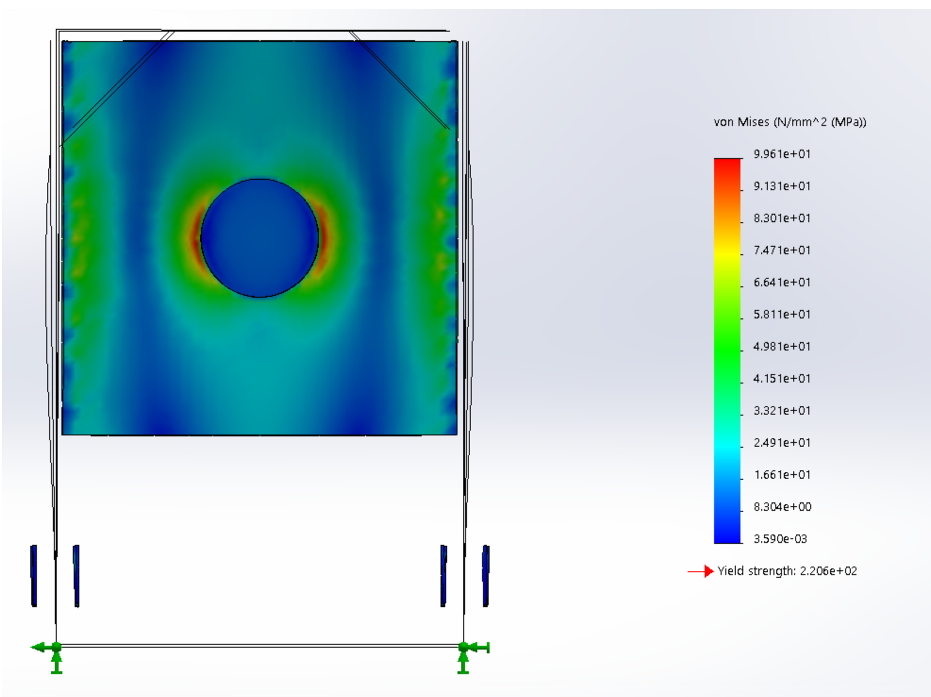


Figure 4.5: Von Mises stress result.

It can be observed an area of higher concentration of stresses around the sides of the circular plate and also a concentration of stresses on the joint axis between the rectangular plate and the supporting beams.

The maximum Von Mises stress present on the plate is of: **99,61 MPa < 235 MPa** (Yield stress).

It is demonstrated that the safety factor on the plate will be of:

$$SF = \frac{\sigma_{vM}}{\sigma_y} \leqslant 1$$
$$SF = \frac{99{,}61}{235} = 0.42$$

It can be so concluded that there is an approximately 50% load on the structure than that which could make it have a fatal failure, for his reason it is safe to affirm that this structure will be capable of supporting such load.

But what about the beams? The beams have been analyzed in the following figure by using a combination of the upper bound axial and bending stresses. They can be observed in the following image:

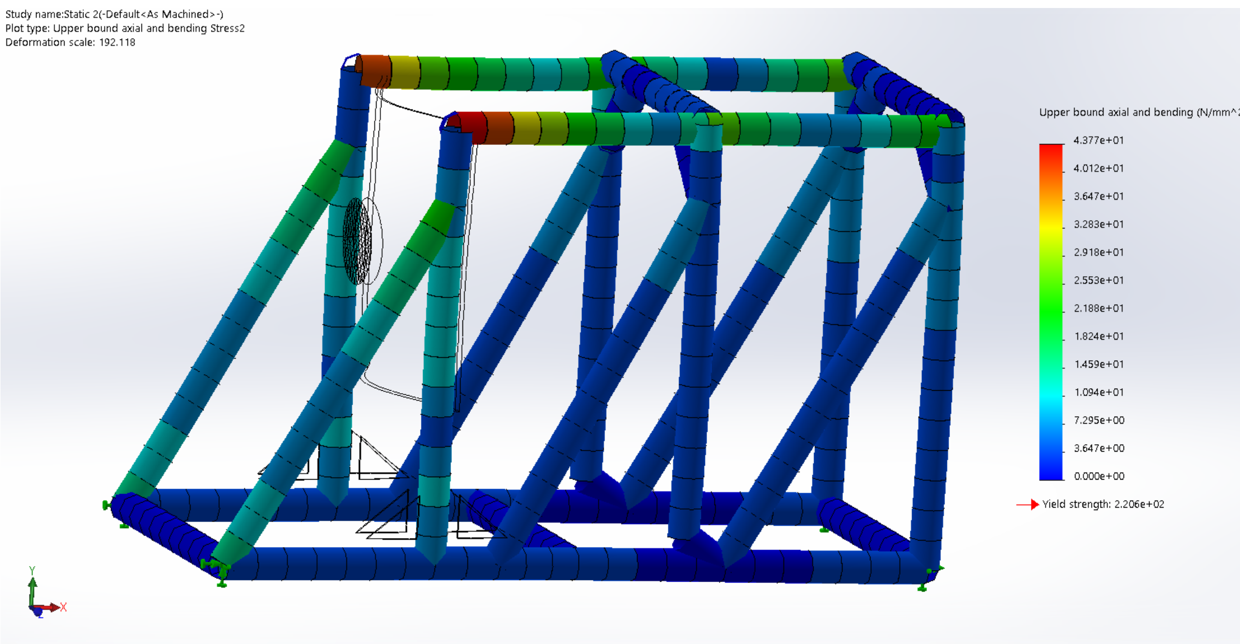


Figure 4.6: Upper bound and bending stresses on the beams result.

It can be observed that the maximum stress is **43.77 MPa** which is far lower than the yield limit of 235 MPa. And the safety limit is:

$$SF = \frac{\sigma_{vM}}{\sigma_y} \leqslant 1$$
$$SF = \frac{43.77}{235} = 0.19$$

It can be concluded that not any of the beams will fail because of a material strength problem, and the material will not deform or brake.

It can be observed that the biggest stresses happen at the joints of the main vertical support beams and the horizontal L shaped beams, precisely in the extreme of these. These is caused because the cross section area of these beams is smaller and they are joined to the loaded plate making they deform as it will be observed in the deformations plot.
The deformations on the plates can be seen:

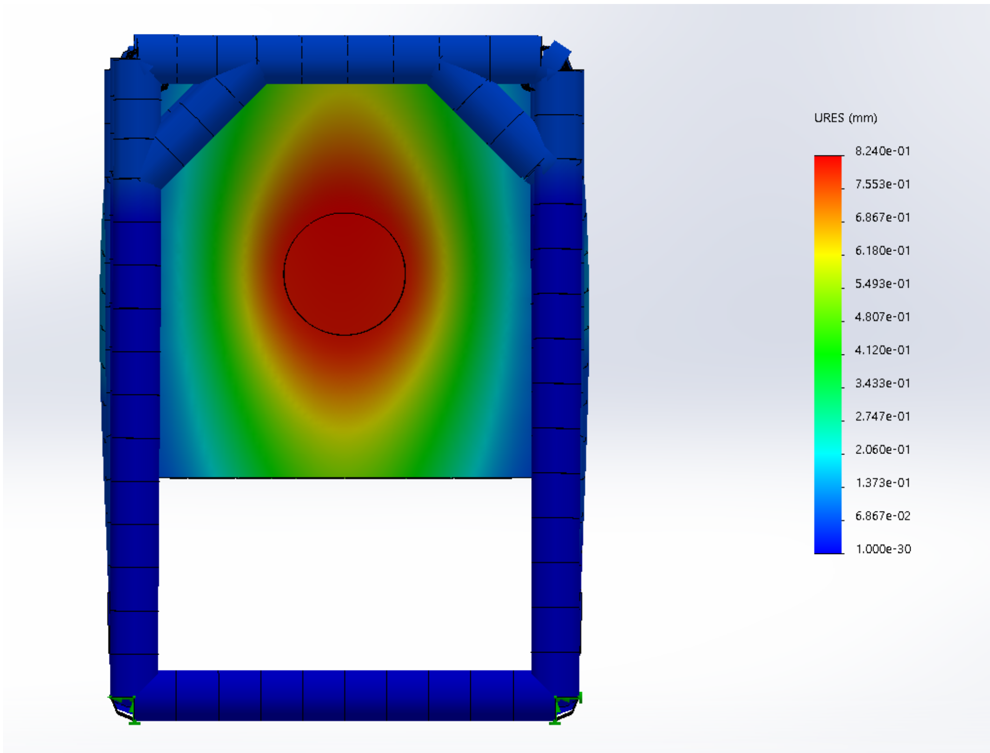


Figure 4.7: Displacements on the structure.

And the deformation on the beams:

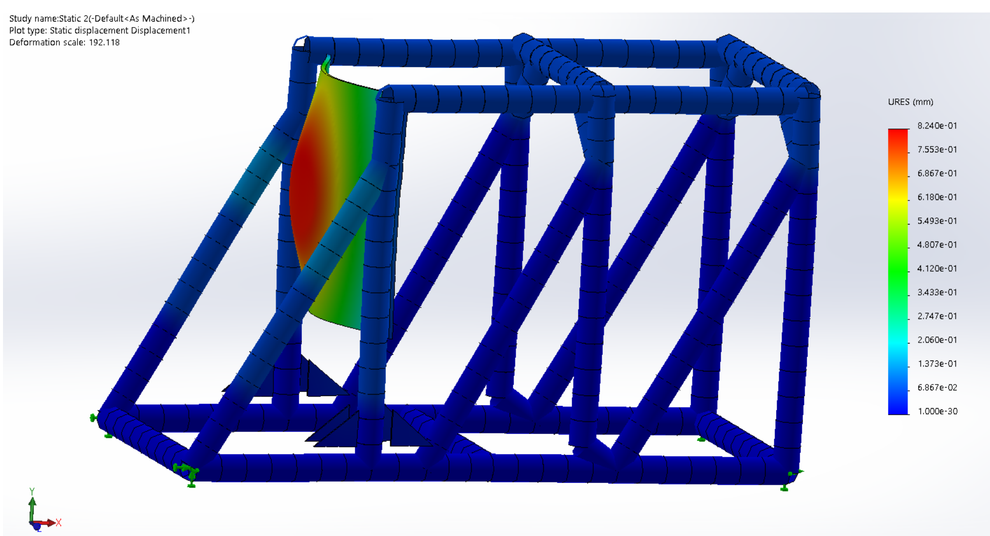


Figure 4.8: Displacements on the structure.

Maximum deformation is **0,824 mm** and it is placed on the loaded plate, where the maximum stresses are located. If a lesser deformation on the plate was desired a solution could be the increase in thickness of the rectangular plate.

Note that NONE of the plots are in real scale.

4.2.2 Buckling analysis

In order to perform the buckling analysis of the beams it must be observed which of the beams are subjected to a tensional state and which to a compression. This can be observed by plotting the axial stresses on the beams as follows:

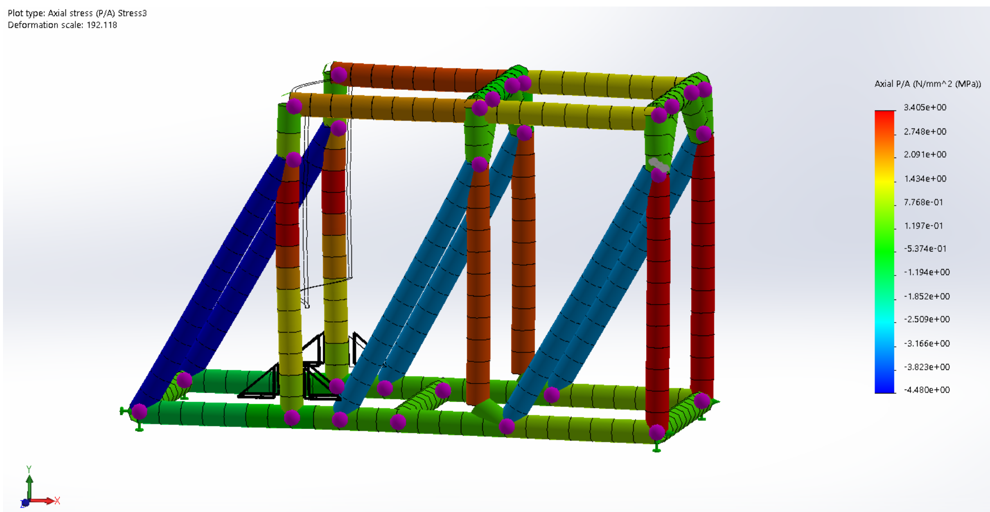


Figure 4.9: Axial stress on the beams.

It can be observed that the beams that could be subjected to buckling are those on blue at the leftmost part of the structure. These are 2 beams with a square cross section of 50x50x3.2 mm and length of 830 mm. These beams are the critical ones as they would be the firsts to buckle.

From the Euler theory of beams under a load it is known that the critical load for a beam under an axial load situation is:

$$P_{cr} = \frac{\pi^2 EI}{(kL)^2}$$

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 E}{(L_e/r)^2} < \sigma_y$$

Where:

- $\frac{L_e}{r}$ is the slenderness ratio
- $L_e = KL$ is the effective length
- $r = \sqrt{\frac{I}{A}}$ is the radius of gyration
- I is the moment of inertia
- A is the cross section
- E is the modulus of elasticity
- L is the unsupported length of the beam
- K is the column effective length factor as shown in the following image.

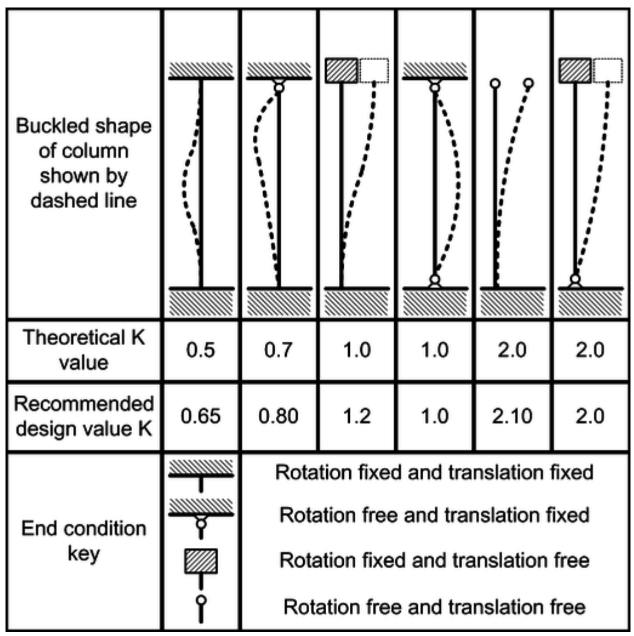


Figure 4.10: Column effective length factors for Euler's critical load. [22]

And to study the effects on buckling on the beams instead of the axial stress, it will be taking into account the bending by using the mixed stress calculation on the static study of upper bound axial and bending stresses which will indicate a bigger value than only taking into account the axial stress, thus making it a more strict criteria for safety reasons.

So the critical load value for buckling under the first mode is:

- E= 210.000 N/mm^2L= 830 mm
- k=0.65
- $I = \frac{50^4}{12} - \frac{43.6^4}{12} = 219.695,92mm^4$
- $A = 50^2 - 43.6^2 = 599,04mm^2$
- $r = \sqrt{\frac{219695{,}92}{599{,}04}} = 19,15mm$
- $L_e = 0.65830 = 539,5mm$

$$\sigma_{cr} = \frac{\pi^2 E}{(L_e/r)^2} = \frac{\pi^2 210000}{(539,5/19,15)^2} = 2611,40N/mm^2$$

$$\sigma_{cr} = 2611{,}40 \text{ N/mm}^2 > 235N/mm^2 = \sigma_y$$

It can be observed that the stress necessary to make the beam buckle under Euler's assumptions would be higher than the yield stress, for this reason the beam would first suffer nonelastic deformations or break before showing buckling behaviour.

Economic viability and budget

In this chapter it is described the monetary resources used for the completion of the project and compared to values pertaining to other projects developed by other organizations or companies. It is studied if the developed solution would be competitive in the market compared to other already present solutions.

5.1 Budget

The costs for this project can be divided mainly into two groups, the cost of the engineering and the cost of the materials. The engineering cost comprises the assets needed to develop the design, write the report and build the test stand, and the material costs would envelope those costs related to the components and materials used in the fabrication of the test stand.

The price of the working hours of the engineer has been calculated from the hypothesis that the annual salary of the engineer without accounting for taxes, is of 24.000 € . Thus, the gross salary per month would be of 2.000€ and the price per hour of 12.5€ .

The costs for the engineering of the design and development of the solutions' report would be the following:

Table 5.1: Engineering costs of the design.

Asset	Duration	Price per hour	Cost
Research and investigation of current technologies	30 h	12.5 € /h	375 €
Development of the design	110 h	12.5 € /h	1375 €
Computational analysis of the structure	75 h	12.5 € /h	937.5 €
Building of the structure and assembly	100 h	12.5 € /h	1250 €
Total cost:			**3937.5 €**

And the materials' costs of the electronic, structural and otherwise components of the test stand would be:

Table 5.2: Material cost of the Electronics Module.

Component	Unit Cost	Quantity	Cost
Arduino Mega	14 €	1	14 €
Load cell YZC-526 1T	35 €	1	35 €
ADC ad7606 converter	36 €	1	36 €
DAAU amplifier	25 €	1	25 €
Sorted cables and electronics kit	11 €	1	11 €
Total cost:			**121 €**

Table 5.3: Material cost of the structure.

Component	Quantity	Longitude [mm]	Cost/Tn [€ /m]	Cost [€]
Beams				
Square beam 120x120x5	1	6000	288	207
Square beam 90x90x5	2	916	288	153
Square beam 50x50x2	2	6000	288	35
L beam 60x60x6	2	6100	1050	72
Plates and others				
Rectangular plates 70x150x16	8			41
Rectangular plate 600x600x8	1			31
Circular plate D180x35	1			12
Circular rings D180x10x26	4			42
Hexagon head bolts A2-70	52			52
Total cost:				**645 €**

By adding the electronics total cost to the structural materials total cost it can be deducted the total price of the build which would be of:

Total price of the stand: 766 €

5.2 Economic viability

There are not many available test stands for middle sized rockets in the market to be bought by particulars or being commercially distributed, almost all of the solutions observed in the state of the art chapter where developed by individuals or organizations to be used within said organizations and not for mass production and distribution to the public. What makes it so is the fact that for many rockets, once they are above a certain size, need a particular stand that is customized to work with such rocket. It is difficult to find a test stand that as the one built and described by the author, can adapt to different length and sizes of motors. Also another big reason is that there is not a big demand on this type of solutions, thus making it almost impossible to mass produce. Usually what it is done is that a certain organization with enough funds designs a bench to test a certain rocket motor or to test a certain type of motors (solid, liquid or hybrid) and then other smaller companies or organizations rent such stand in order to test their own motors.

Even though it has been found a closely similar product available on the web to which compare the price point of the developed solution. It is a rocket test stand developed by Aerocon Systems, a company located in San José, California (United States). Although Aerocon Systems works in collaboration with big companies such as Boeing, SpaceX or Airbus, it is a company originated from amateur rocketry and that still sells products and solutions to the amateur rocket community.

Figure 5.1: Aerocon members of the company at work in the Mojave desert. [23]

The product available from Aerocon is a rocket test stand developed to be able to be compatible with rockets with a diameter of 38 mm, 54 mm, 75 mm or 98 mm. Each diameter needs different clamps that must be bought additionally though. Also, the load cell can be chosen from a wide variety with the biggest load capacity of them being at 500 kgf.

The stand is divided in two parts that must be bought separately, the Horizontal/Vertical Test Stand and the Data Acquisition package. The prices are:

Table 5.4: Aerocon test stand cost. [24]

Component	Characteristics	Cost
Horizontal/Vertical Test Stand with 98 mm clamps	The angled braces are each rated for 1,200 pounds force each. That coupled with the corner bracing the stand should be able to take 2,500 pounds force, but it is recommended no more than 1500 lbf (680 kgf). 98 mm clamps are provided. Total weight of the stand is approximated 55 pounds.	592 $ (534 €)
Data Acquisition package + 500 kgf Load Cell	The maximum capacity load cell for available on this company is of 500 kgf. The specifications of the data acquisition module from Aerocon for the basic package are the following: Supply from 9V batteries. Force single point shear beam load cell of 500 kgf. 2mV/V Non-linearity(%F.S) : .03% Hysteresis(%F.S) : .03% Repeatability(%F.S): .02% Four ±10 V Differential Analog Inputs. 12-bit Resolution. High sample rates per channel (dependent on the number of channels enabled): 40 kHz (1 enabled channel) 30 kHz (2 enabled channels), 24 kHz (3 enabled channels), 20 kHz (4 enabled channels).	353 $ (319 €)
Total cost:		**945 $ (854 €)**

Figure 5.2: Aerocon Test Stand structure with a 98 mm rocket motor mounted. [24]

Figure 5.3: Aerocon Data Acquisition package number 1. [25]

As it can be observed the price of the data acquisition module from Aerocon (319 €) is way higher than that developed by the author (121 €), which makes it a better solution for our requirements and it can also be assessed a good viability in the market.
It must be noted though that the specifications and characteristics of both systems are different and that the characteristics of the module sold by Aerocon make it probably better in the case that you need more precision, resolution or more channels to use different load cells or transducers.

Regarding the cost of the structure, it can be noted that the structure from Aerocon is cheaper than that built in this project, but it comes with a list of disadvantages as the solution developed from Aerocon is not as robust as the one designed here. The performance and capabilities of Aerocon's stand are way under the capabilities of the developed solution. The Aerocon's solution is a smaller test stand which is capable of testing motors up to 680 kgf, while the developed solution is capable of testing thrust levels of almost double the capacity (1000 kgf and possibly more). It is observed that Aerocon's test stand is lighter and smaller, which would be a good solution for smaller motors. Put into perspective the capabilities that are given by the developed solution justify its difference in price, while the difference in prices is not too much as it is only a matter of **111** €.

All in all, it has been demonstrated the viability of the proposed solution and the competitiveness of its costs compared to other solutions present in the market. It has been demonstrated that the raw costs of the materials are well under those of buying a pre-made solution, but if the engineering costs should be added, then it might not be such a good solution. For the use intended in this thesis, which is for personal use by the creator, where the engineering costs are not paid as the client is the developer, this solution is deemed appropriate and very cost effective.

Operational Normative and Safety Rules

In the future this test stand will have to be operated and it is important to set good operational procedure to avoid creating any dangers or unnecessary risks.

It has been studied the normative applicable to high power rocketry NFPA 1127. This code and standards set a list of guidelines for operating high power rockets and while it does not mention using test stands to test the rockets it is used for launches of high powered rockets.

For this reason it is necessary that all the operators have read it, understood it and follow it during the operation of this test stand. Some of these guidelines, but not all, are written in the following, for more guidelines and recommendations please see [30].

4.2 User certification. Only a certified user shall be permitted to launch a high power rocket.

4.4.1 A high power rocket shall be inspected by the Range Safety Officer (in a preflight inspection) to determine whether it meets the provisions of this code.

4.12.2 The launching device shall incorporate a get deflector if necessary to prevent the rocket motor exhauste from impinging directly on flammable materials.

4.13.1 A high power rocket shall be launched using an ignition system that is remotely controlled, is electrically operated, and contains a launching switch that returns to the "off" position when released.

4.13.6 A high power rocket shall be pointed away from the spectator area and other groups of people during and after installation of the ignition device.

4.15.1 The area that encircles a launch pad shall be cleared of brown grass, dry weeds, and other easy-to-burn materials for a diameter equal or at least that specified in the following table:

Table 6.1: Minimum clear distances. [30]

Installed Total Impulse [N·sec]	Launcher Equivalent Motor Type	Minimum Clear Distance [m]
0-160	G or smaller	0
160-320	H	50
320-640	I	50
640-1280	J	50
1280-2560	K	75
2560-5120	L	100
5120-10240	M	125
10240-20480	N	125
20480-40960	O	125

4.19.2 Not more than 23kg (50lb) of net rocket propellant weight of high power rocket motors, motor reloading kits, or pyrotechnic modules subject to the storage requirements of 27 CFR 55, "Commerce in Explosives" shall be stored in a type 3 or type 4 indoor magazine.

The list could carry on as there are other items as important as the ones listed. For this reason it is imperative to have read the complete guidelines before operating the test stand.

Conclusions

The objective of designing and constructing a middle sized rocket motor test stand has been achieved and therefore this project can be called a success.
It has been studied the state of the art and previous history regarding the construction of test stands for rockets. Also it has been reviewed the different designs present in the aerospace community and related organisations and administrations. Thereafter it has been made a preliminary study to obtain some design parameters and requirements that the test stand should comply with.

Different designs have been made with different orientations and approaches before arriving to the design chosen for a number of before mentioned reasons.

The electronic part of the stand was approached and a study of alternatives was done in order to arrive to the most cost effective solution. Then the electronics were put together and it was checked that the system worked as predicted.

The final design was subjected to a number of studies to certify its operational capacity with the use of computer aided numerical methods, in particular the Finite Element Analysis approach. The obtained results were acceptable and it was simulated the good performance of the structure under load conditions.

Then the design was built by the use of commercially available materials and the process was described. Also the suitability of the material was studied.

The economic budget certified the economic viability of the project and finally some operational rules and guidelines were indicated for a future operation of the test stand.

Even though this work contained a lot of different subjects and dealt with many different issues, it must be said that there are still some activities to perform before the test stand is called complete.

These activities were not under this project scope and could be performed in another project, thesis or work.

All in all, it can be said that the results of this work have been positive, and although it might not be the most optimized test stand in regards to weight, construction method, design or otherwise, it achieved good results and should be able to be operated in the future successfully.

7.1 Future work and perspectives

The future work that was left pending at the end of this project is the following, this section is useful in order to indicate and describe lightly the following necessary and compulsory activities to be carried out:

- Calibration of the sensors: the load cell is operational after this project but when mounted to the test stand needs to be calibrated. There are two approaches to calibration, physical calibration which is assuring that the cell is not subjected to any offset loads as weight or an initial tensional stress, also making sure that there are no frictions or elements that can alter the readings; then there is the software approach which is the analysis of the results and from the testing with various known weights or loads, the substraction of the forces that do not come from the rocket motor, as offsets or noise.
- Thermal study and thermal protection of the parts and terrain that is subjected to the fumes of the rocket motor. It is necessary to comply with the safety normative and to operate safely that no flammable materials are on the vicinity or in the stand, and if so that they are properly shielded.
- Protection shield or plate, this was commentated in this project but not yet designed and built for a lack of resources. It is necessary that a safety perforated plate to protect from shrapnel.
- The suitable rocket must be constructed or bought and a preflight analysis of the hypothetical performance and behaviour studied, static analysis and dynamic analysis.
- Ignition systems must be studied and applied to the rocket motor.
- **Testing of the test stand under real conditions with the necessary safety precautions.**

All in all, it can be said that this is a very complex project with a lot of improvements that can be done and with a bright future and good prospects based in the results obtained in this study. For this it is concluded that this has been a very rewarding experience, which made the author learn a lot and expand his knowledge into different fascinating rocketry related areas.

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